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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Articles submitted for publication to the JOURNAL OF SEDIMENTARY PETROLOGY should have a prefatory abstract and sufficient postage should be sent by the author to prepay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 5, NO. 2, PP. 57–80, TABLES I–V,
AUGUST, 1935.

THE BOTTOM DEPOSITS OF SOUTHERN LAKE MICHIGAN ✓

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ABSTRACT

Quantitative data on the sediments are presented, along with a discussion of their environment, sources, and agents of transportation. Maps show bottom topography and areal distribution of sediments, and diagrams illustrate relations between mechanical composition and bottom topography.

Bottom sands of both the eastern and western shore terraces of the lake show a coarsening in size as the depth of water and distance from shore increase. A gravel-veneered till bottom is common in the western and southern parts of the lake; the gravel is interpreted as a lag concentrate of the coarser constituents of the till, produced by wave and current action. Sand derived from the till is apparently carried toward shore in most localities, while the finer fraction of till is deposited as a soft gray clay in the deeper parts of the lake. In the Chicago area, sand occurs in broad low ridges which are nearly parallel with shore, while gravel veneered till is found in the hollows between the ridges. This topography may be largely inherited from a time of low water, but the characters of the sediments indicate important present-day action on the bottom.

INTRODUCTION

Statement of the Problem.—The primary purpose of this study was to collect quantitative data on modern sedimentation in a large body of water. Since progress in the interpretation of ancient sediments depends largely upon the growth of knowledge of sedimentary processes, it is highly desirable to collect data on the areal distribution, texture, and composition of bottom materials which are still undergoing erosion, transportation, and deposition.

Aids Received.—The boat which was used in the work was put at the disposal of the author by Prof. A. J. Carlson of the University of Chicago who also made available the facilities of the machine shop of the Physiology department for construction of bottom sampling apparatus. The purchase of necessary materials was financed by a grant of the American Academy of Arts and Sciences.

Previous Investigations.—The U. S. Lake Survey has made and published numerous soundings of Lake Michigan.[1] The charted information on the character of the bottom material is, however, always meagre and very general in nature. A biological investigation of the deep water fauna of Like Michigan, made by Stimpson in 1870,[2] gives some information of the bottom in the regions studied. The modern investigation of the sediments of the Lake Michigan basin, from the geologist's point of view, was initiated by Pettijohn in his study of the beach sands of Southern Lake Michigan.[3]

FIELD AND LABORATORY METHODS

Field Equipment.—The boat used for the collection of samples was a

[1] *U. S. Lake Survey*, charts No. 7, Lake Michigan; 70–79, Coast Charts; 753–754, Chicago lake front charts.

[2] Stimpson, Wm., On the deep water fauna of Lake Michigan, *Am. Naturalist*, vol. 4, pp. 403–405, 1870.

[3] Pettijohn, F. J., Petrography of the beach sands of southern Lake Michigan, *Jour. Geol.*, vol. 39, pp. 432–455, 1931.

fairly seaworthy 25-foot sloop-rigged dory. Sampling operations were dependent upon the weather since the boat had no inboard auxiliary power though in the event of too light a wind and a calm sea, an outboard motor was clamped on a bracket at the stern. The sampling apparatus was hauled aboard by hand except in deep water when a hand windlass was used. Two types of bottom sampling apparatus were found most useful in this work. These were a *clamshell snapper*,[4] a device consisting of two jaws and a strong spring with a catch, which closes automatically on striking any fairly hard bottom, and a modified *Ekman sampler*,[5] consisting of a tube and a vertical check valve, which takes a core sample of any fairly soft bottom.

Field Methods.—By sailing a compass course and measuring the distance run with a boat log the sampling stations were located. In addition a few locations were obtained by compass sights on known landmarks. When the boat log registered the desired "distance run," the boat was luffed (headed into the wind) and as soon as sufficient headway was lost the sampler was dropped overboard from the cockpit, and hauled aboard again as soon as it had struck bottom. In the meantime it was necessary for the helmsman to keep the boat from "falling off" the wind and sailing away. The contents of the clamshell snapper were emptied into a bucket while those of the Ekman apparatus were put into a Mason jar. Samples were stored in Mason jars until they could be dried on a hot plate in the laboratory, after which they were stored in cardboard cartons. Core sections from the deeper part of the lake were transferred to cardboard mailing tubes which had been slit up one side and laid open. The tubes were then carefully wrapped in waxed paper.

Laboratory Methods.—The samples of the sandy sediments were halved with a Jones sample splitter until reduced to about 25 grams each. The weighed sample was then sieved for 15 minutes with a Ro-tap machine in a nest of Tyler woven wire screens having the following sized openings: 1.40 mm., 1.00 mm., 0.71 mm., 0.50 mm., 0.35 mm., 0.25 mm., 0.177 mm., 0.125 mm., 0.088 mm., and 0.061 mm. The separated fractions were then weighed, and their percentage of the whole sample calculated. (Tables II to V). Samples of silt and clay were reduced by quartering, the alternate quarters being rejected, until a sample weighing about 15 grams was obtained. The weighed sample, shaken in water to which a half-gram of sodium carbonate was added to insure dispersion, was transferred to a screen such that material larger than one-sixteenth millimeter in diameter was retained, to be later dried and weighed, while the material smaller was washed through and diluted so as to make a liter of suspension to be analyzed by the pipette method.[6] The data obtained were

[4] Soule, F. M., Oceanography, *National Research Council, Bull.* 85, pp. 433–435, 1932.

[5] Similar in principle to the "Meteor" tube sampler. *Op. cit.* pp. 435–436.

[6] "This method rests on the principle that in a dilute suspension the particles fall as in-

plotted as cumulative curves, and the median and quartile values graphically determined.

ENVIRONMENT OF THE SEDIMENTS

Physical Characteristics of the Basin.—Lake Michigan, the third largest of the Great Lakes in point of surface area and the second in point of depth, lies between 84°50′ and 88° West Longitude and between 41°35′ and 46°05′ North Latitude. The principle dimensions, surface elevation, and rainfall of the region are as follows:[7]

Physical Characters of the Lake Michigan Basin

Length (straight line)	307 miles
Breadth (straight line), on about 45°25′ north latitude	118 miles
Breadth, average	70 miles
Depth, maximum recorded by U. S. Lake Survey,	923 feet
Water surface of lake	22,450 sq. mi.
Entire drainage basin	60,150 sq. mi.
Mean surface, 73 years, 1860–1932, above mean sea level	580.87 feet
Rainfall, average annual	32 inches

The lake has the general form of a trough, but is made up essentially of two basins separated by a transverse ridge. The depth of 923 feet, given above, occurs in the northern basin, while the maximum depth of the southern basin is 564 feet. The average depth of water on the transverse ridge is 270 feet. The portion of the lake which is included in the present study lies south of a line between Milwaukee, Wisconsin, and Grand Haven, Michigan, and includes the southern basin. The bottom topography of this southern basin is simple, as may be seen from the map, Figure 1.

The greater part of the Lake Michigan basin is a trough following the strike of relatively weak Devonian shales and siltstones which lie between more resistant Niagaran limestones of the western and northwestern shores of the lake, and the Mississippian sandstones and shales of the eastern or Michigan shore. The bedrock of western Michigan is much more deeply buried beneath glacial drift than is that of eastern Wisconsin, and the position of the eastern shore of the lake is more closely controlled by deposits of drift than by the bed rock.

The water of the lake, perfectly fresh at all depths, supports a fauna which is characteristically meagre in comparison with that of a salt water environment. Rooted plants are practically absent from the lake bottom, except in protected embayments.

Currents.—The enormous volume of water in the lake assures comparative stability of the entire mass since both the inflow and outflow are relatively small. It has been estimated that only one-eighth of the

---

dividuals, and by permitting all grains having a given velocity to settle below a certain level, a sample taken at that level at the critical time will contain the full concentration of all material having a lesser velocity. By taking samples from the given level at various intervals, the concentrations of successively smaller particles may be found, and by subtraction the amount of material in any grade may be computed. The samples are . . . 20 cc., and the suspension is well shaken between samplings." Krumbein, W. C., A history of the principles and methods of mechanical analysis, *Jour. Sed. Petrology*, vol. 2, p. 111, 1932.

[7] Survey of northern and northwestern lakes, *U. S. Lake Survey*, Bull. 42, p. 122, 1933. Also Schermerhorn, L. Y., Physical characters of the northern and northwestern lakes, *Am. Jour. Sci.* (3), vol. 33, pp. 278–284, 1887.

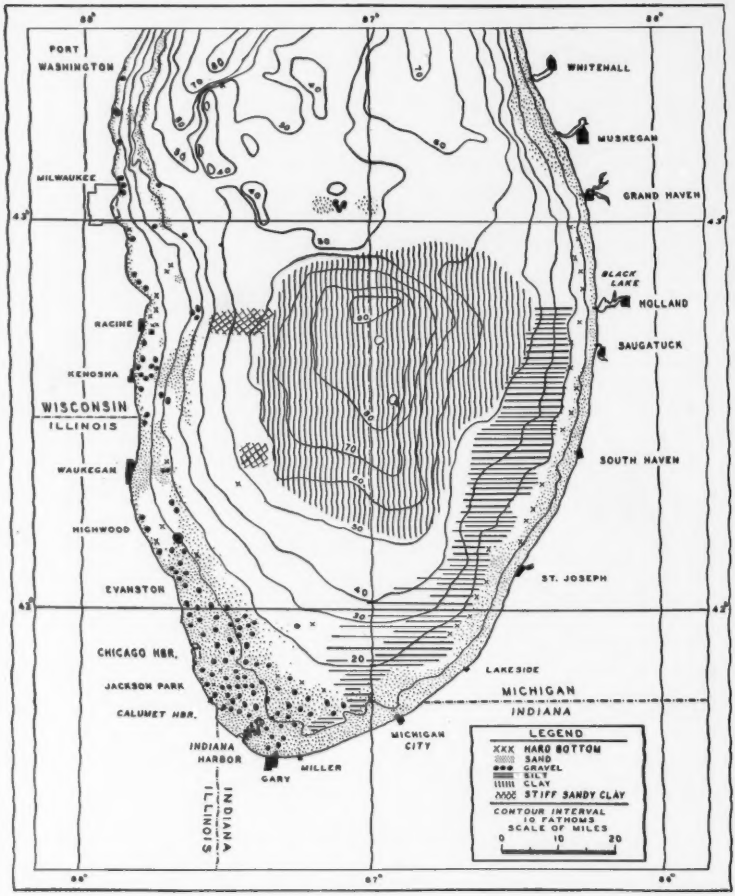

FIG. 1. A reconnaissance map of the southern part of Lake Michigan, showing the areal distribution of the sediments as determined from the samples collected in the present study and from the notations on the base map. Contours drawn from the data of the base map, U. S. Lake Survey chart No. 7, 1931.

entire volume of Lake Michigan is changed in one year.[8] A gentle body drift must result from this change of water.

Surface currents are produced primarily by wind action, and these are often accompanied by bottom cur-

[8] Ward, H. B., A biological examination of Lake Michigan in the Traverse Bay Region, *Mich. Fish. Commission*, 12th Bienn. Rept., p. 9, 1896.

rents in the opposite or some other direction. The shape and orientation of the lake basin and the direction of the prevailing winds are the most important factors of current control. A study of the surface currents of the Great Lakes was made by Harrington by means of drift bottles, which were released at various points in the lakes and recovered at their points of stranding on the shores. His conclusions regarding Lake Michigan may be summarized as follows:

> There is a southward drift along the whole of the western side of the like, which continues around the south end and turns northward on the eastern side, becoming more pronounced. Around the Beaver Island group in the northern end of the lake there is a counterclockwise swirl, and in the major southern basin there is a similar swirl. Between these two areas there is a tendency for the surface water to move eastward along lines which are curved with their convex sides to the south.[9]

Townsend criticized these views and pointed out that since only the point of release and the point of recovery of a bottle are known, it is not possible to know the path taken. Townsend believed that the conception of a swirling movement in the southern basin is without sufficient evidence.[10]

The U. S. Bureau of Fisheries has recently made an investigation of the surface currents of Lake Michigan, also using drift bottle apparatus. In a preliminary report the following conclusions are given:

> Along the east shore of Lake Michigan the current tends to move northward at an average rate of several miles a day. Bottles set adrift on the west shore of the lake show a tendency to move over toward the east or Michigan shore and then move northward. In the southern part of the lake in the area south of Waukegan and St. Joseph the drift bottles showed a very irregular movement indicating somewhat of a swirling action in that area. Bottles released in that area were usually out a very long time, which seems to indicate that they followed a very wide and indeterminate path before reaching their destination. The point of recovery was often less than fifty miles from the point of release although the bottles were out thirty days or more.
>
> There is little doubt but that the action of the prevailing westerly winds in Lake Michigan has much to do with the rate of and direction of the surface currents. The prevailing westerly winds coupled with the general direction of flow toward the outlet into Lake Huron may be predicted as the cause of the northerly current along the east shore and the tendency to move from the west to the east shore. More detailed information concerning these surface currents will be available when the data at hand have been interpreted in connection with meterological data. . . .[11]

The accumulation of shore drift on the north sides of artificial breakwaters and groins which extend out from shore has been cited as evidence of the existence of southward-moving littoral currents along both shores of the lake. A mineralogical study of the beach sands of the region, made by Pettijohn,[12] also indicates that the direction of transportation of the beach material is southward. Cressey[13] credits littoral currents on the two sides of the lake with the trans-

[9] Harrington, M. W., The surface currents of the Great Lakes, *U. S. Weather Bureau*, Bull. B., 1895.

[10] Townsend, C. McD., The currents of Lake Michigan and their influence on the climate of the neighboring states, *Jour. West. Soc. Engineers*, vol. 21, pp. 293–309, 1916.

[11] Deason, H. J., A study of the surface currents in Lake Michigan, *The Fisherman*, vol. 1, p. 12, 1932.

[12] *Op. cit.*, pp. 441–455.

[13] Cressey, G. B., The Indiana sand dunes and shore lines of Lake Michigan, *Geog. Soc. Chicago*, Bull. 8, p. 18, 1928.

portation of all the sand which reaches the beach at the Indiana Dunes.

Seiche currents, caused by a difference in the atmospheric pressure over opposite ends of the lake, rarely produce any considerable displacement of the water level. Changes in level of a few feet, however, have been recorded. Lunar tides in the lakes are of insignificant magnitude, averaging about two inches.[14] Tidal currents, therefore, are practically non-existent.

The bottom currents of the lake, which are more directly concerned with the transportation of bottom sediments, have not been investigated. It is very likely, however, that strong bottom currents exist under certain weather conditions. Kindle has described some striking currents in Lake Ontario.[15]

Effect of Temperature on Circulation of the Water.—Temperatures in Lake Michigan have a rather wide range in the surface waters, varying from the freezing point to 55° or 60° F. In contrast, the water of the deeper levels (generally, below 300 feet) maintains a nearly constant temperature throughout the year; the temperature is that at which water reaches its maximum density, 39.2° F. or lower, depending on the pressure.[16] With this distribution of temperatures it may be assumed that circulation is confined to the upper layers during the warmer months of the year, and is complete only when the temperature of the entire mass reaches the point of maximum density.

Wave Action.—The author has observed waves in Lake Michigan (in October, 1928), 30 miles from the nearest shore, and 85 miles from the windward shore, which reached a height of over 15 feet and a length of over 100 feet. These estimates were made with a 64-foot schooner as a measuring-stick, and are not excessive. Waves of similar size have been observed in Lake Superior.[17] A recording device set up on a breakwater at Milwaukee, Wisconsin, failed to record waves higher than six feet during a two-year period from 1930–1932.[18] However, the breakwater is protected to a certain extent by headlands to the north and to the south, and by a wide subaqueous terrace. At Michigan City, Indiana, on the southeastern shore, the author has seen 12-foot waves washing over the breakwater. A storm occurred on November 31, 1934, which enabled rather accurate measurements of wave length to be made. This storm drove a large vessel against the breakwater at Muskegon, Michigan. An aerial photograph of the vessel and lake at this time[19] clearly showed waves beating against the wrecked vessel. Since the length of the ship is known, caliper measurement of

[14] Schermerhorn, L. Y., *Op. cit.*, p. 284.

[15] Kindle, E. M., Bottom deposits of Lake Ontario, *Roy. Soc. Canada, Trans.*, 3rd. ser., vol. 19, pp. 30–37, 1925.

[16] Wright, S., Bottom temperatures in deep lakes, *Science*, (n. s.) vol. 74, p. 413, 1931.

[17] Cornish, V., *Waves of the sea and other water waves*, London, T. Fisher Unwin, p. 33, 1910.

[18] Caples, Col. W. G., U. S. Engineers Office, Chicago, Ill., personal communication.

[19] *Chicago Sunday Tribune*, Part I, p. 3, Dec. 2, 1934.

the ship gives a definite scale to which identical measurements of visible waves can be compared. By this method an average wave length of 160 feet was obtained.

SOURCE MATERIALS OF THE SEDIMENTS

Glacial Drift.—The unconsolidated till and stratified sand which occur in such abundance along the shores (and in some cases on the lake bottom) doubtless contribute most of the material found in the lake sediments. The easily-erodable nature of the drift, and the great preponderance of erratic rocks and minerals in the sediments show the importance of this source.

River-Borne Material.—The rivers which empty into the lake apparently play a minor rôle as contributors of sediment. The land area of the entire drainage basin is but slightly more than twice the surface area of the lake; most of the rivers are, therefore, comparatively short. In addition, the relief of the land is comparatively low. Silt and clay particles are undoubtedly carried into the lake in some quantity, along with organic material, but the longest rivers, on the eastern side of the lake, must drop most of their loads in the drowned lower portions of their valleys before they enter Lake Michigan.

Bed Rock.—Glacial ice apparently planed down all of the outcrops of weak rock in the region before Lake Michigan was formed, and the only rocks which are left exposed to the waters of the lake are quite resistant to erosion. There is some evidence that bed rock, probably Mississippian sandstone, outcrops on the bottom along the eastern side of the lake at a distance of 3 to 5 miles from shore. Several areas of Niagaran limestone occur near the western shore, expressed as shoals. These occurrences of bed rock will be described in greater detail later. In general, it is believed that the bed rock supplies a very small proportion of the sedimentary material.

THE SEDIMENTS OF SOUTHERN LAKE MICHIGAN

Beach Sands

The eastern shore is a sand beach, with occasional patches or zones of gravel and rarely boulders at the shoreline. The beach is bordered by sand dunes along most of its extent, but occasionally a cut cliff occurs in stratified sand or in glacial till. At the south end of the lake the sand dunes reach their maximum development. The western shore of the lake is characterized by a narrow sand beach, frequently bordered by glacial till cliffs, and occasionally by till cliffs overlain by stratified sand, and the gravel is of more frequent occurrence than on the eastern shore. Along an eight mile stretch north of Waukegan, Illinois, a beach ridge is bordered by swamp-lands. From Evanston, Illinois, southward the lake is bordered by the low broad Lake Chicago plain. The position of the present shoreline of Chicago is due largely to artificial filling and to some extent to the influence of breakwaters and groins on littoral

TABLE I. *Median Diameters of Beach Samples (From the Beaches of Lake Michigan)*

	Beach sample No.	Locality[1]	Median in Millimeters
	61	Highwood, Illinois	.288
	40	Winnetka, Illinois	.216
Western	39	Kenilworth, Illinois	.235
beaches	63	Rogers Park, Chicago, Ill.	.199
	65	Clarendon Beach, Chi., Ill.	.200
	55	78th Street, S., Chi., Ill.	.213
	52	Miller Beach, Indiana	.216
	58	Baileytown Beach, Indiana	.306
	53	Waverly Beach, Indiana	.320
	60	Michigan City, Indiana	.310
Eastern	57	Grand Beach, Michigan	.299
beaches	34	Lakeside, Michigan	.300
	45	St. Joseph, Michigan	.306
	46	Benton Harbor, Michigan	.304
	48	South Haven, Michigan	.290
	Sa. 0	Saugatuck, Michigan	.280
	B.L. 0	Black Lake, Michigan	.274

[1] Localities given in order, from the northernmost on the western shore, around the south end of the lake, to the northernmost locality on the eastern shore. The map, Fig. 1, gives some of these localities; refer to Pettijohn's article (*Op. cit.*) for the exact location of all samples.

drift. Wherever natural beaches remain they carry sand or sand and gravel at the shoreline and sand on the bottom to depths of 15 or 20 feet; beyond these depths the character of the bottom is variable.

The mechanical composition of the beach sands was worked out by Pettijohn.[20] Recently, when a new set of screens which gave twice as many grades within the same size range became available, Dr. Pettijohn turned his samples over to the author for reanalysis. To this collection were added samples taken near Saugatuck and Black Lake, Michigan. The data of the original study did not give sufficient points on the cumulative curves for the calculation of the median values of the samples, but the new data makes the computation of this characteristic possible. (See Table I.)

[20] *Op. cit.*

The sands of the western shore, disregarding the Highwood sample, have a median diameter range of from 0.199 to 0.235 mm., and an average of 0.213 mm. The median diameters for the eastern shore range from 0.274 to 0.320 mm., and average 0.299 mm. From Highwood southward to Rogers Park, on the western shore, the median value tends to decrease; from Rogers Park to Miller, at the south end of the lake, there is a slight but steady increase. Between Miller and Baileytown Beach, on the Indiana shore, the size of the sand increases markedly, but beyond Baileytown Beach the median begins to decrease. The coarsest sample was taken at Waverly Beach, and the finest at Black Lake, north of Saugatuck, Michigan, while the samples taken between these two points are intermediate in median size. This northward decrease

in size, and that occurring between Miller and Rogers Park on the western shore, do not support the concept of a southward littoral drift, if it is assumed that a decrease of size in the direction of transport always occurs.

General Areal Distribution of Bottom Sediments

A reconnaissance map of the southern part of Lake Michigan, based largely on the data collected by the author and supplemented by the data of the U. S. Lake Survey charts, is shown in Figure 1. The latter information was, in some cases, usable only when interpreted in connection with that of the present study. For instance, the designation "clay" on the charts may refer to a soft present-day deposit of clay, or to glacial till, or to a rather coarse-grained silt. Where reliable information on the character of the bottom materials is lacking, the map is left blank.

In the eastern half of the area the sequence of sand, silt and clay occurs. The sand is usually found within 3 or 4 miles of shore, the silt is found beyond the sand, and the clay occurs in the deeper parts of the lake, generally below 250 feet. The sand deposits do not show a regular gradation in texture from shore outward, as will be shown later. Occasional occurrences of "rock" or hard bottom are shown along the boundary between the sand and the silt.

In the western half of the area there is a different and more varied assemblage of bottom types, so that no general statement can be made regarding their distribution. A gravel or gravel-veneered till bottom is of widespread occurrence, alternating with patches of sand. The distribution of this material is not as simple as was supposed when the author mentioned this area in a discussion a few years ago.[21]

Texture of the Sediments near the Eastern Shore

Samples spaced at about one mile intervals were taken at Michigan City, St. Joseph, South Haven and Saugatuck, in a direction roughly perpendicular to the shore. The average number in a series was six. In addition, two samples were taken west of the entrance to Black Lake at distances of five and ten miles from shore, and one sample was taken fifteen miles offshore from Saugatuck. The beach samples from these localities are included in the series.

When the grain sizes of the several samples (Table II) are compared with the distance from shore it is seen that the average size of the sediment first decreases with increasing distance from shore, then increases markedly, becoming even greater than that of the beach material in three out of four cases (Fig. 2). Still farther from shore the average size of the material drops abruptly into the silt range, and then grades into a fine clay. The lack of continuous outward decrease in grade size in the sand zone is not consistent with the statement commonly made,

[21] Hough, J. L., Suggestion regarding the origin of rock bottom areas in Massachusetts Bay, *Jour. Sed. Petrology*, vol. 2, pp. 131–132, 1932.

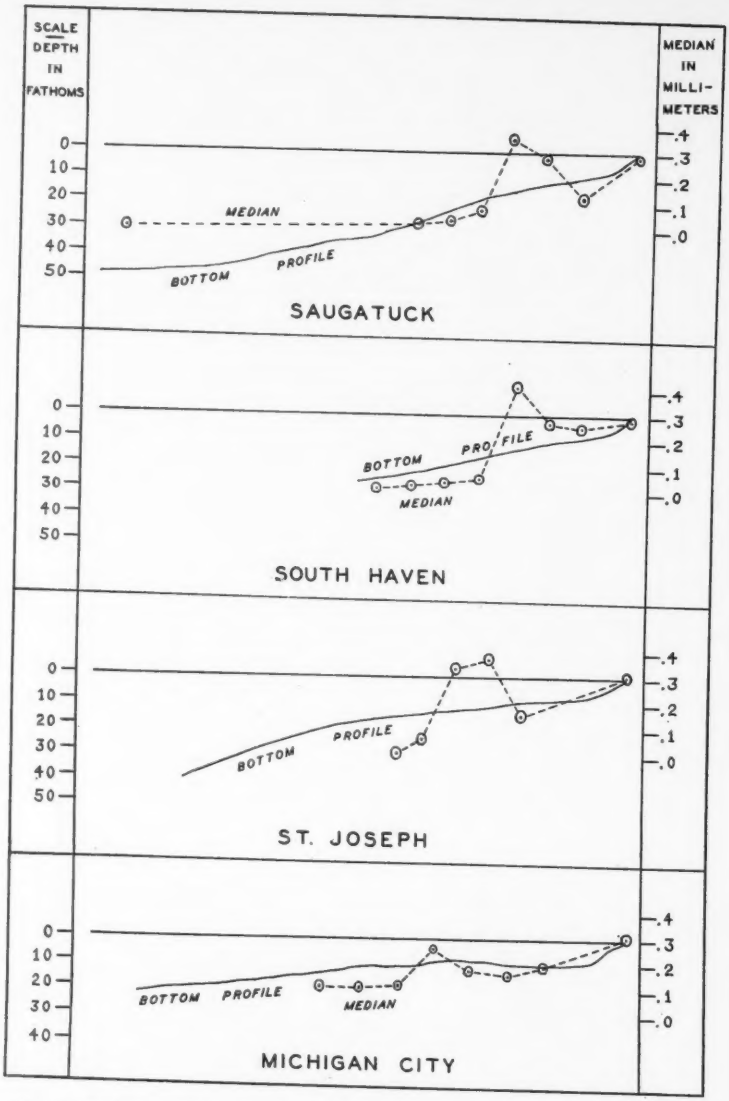

FIG. 2. Profiles drawn on the sampled lines, roughly perpendicular to the eastern shore. Graphs of the median values of the samples are superimposed. Length of the Saugatuck Profile is 15.7 miles; others drawn to the same scale. (See Table II.).

TABLE II. *Mechanical Composition of the Sediments Near the Eastern Shore*

Sample No.	Distance from shore in miles	Depth of water in feet	Per Cent by Weight in Each Grade Size. Grade Sizes in Millimeters. Over 1.40	1.40–1.00	1.00–.71	.71–.50	.50–.35	.35–.25	.25–.177	.177–.125	.125–.088	.088–.061	.061–.031	.031–.0233	.0233–.0156	.0156–.0117	.0117–.0078	.0078–.0040	.0040–.0020	.0020–.0010	.0010–.0005	Remainder*
FJP.60	(Beach)	0	—	tr	1.0	6.4	24.7	46.7	15.9	4.8	tr	—	—	—	—	—	—	—	—	—	—	—
M. 16	2.2	58	.1	.1	.2	.5	2.4	15.4	43.0	32.5	4.2	1.0	.3	—	—	—	—	—	—	—	—	—
M. 10	3.1	56	.1	tr	.2	.5	2.0	10.6	26.1	41.5	16.6	1.6	.6	—	—	—	—	—	—	—	—	—
M. 11	4.1	48	—	tr	.1	.6	5.0	18.8	32.6	31.3	10.3	.6	.3	—	—	—	—	—	—	—	—	—
M. 12	5.1	52	.2	.5	1.6	8.2	18.0	26.0	28.3	13.4	2.7	.2	.3	—	—	—	—	—	—	—	—	—
M. 13	6.0	64	—	—	—	.9	5.4	14.2	8.8	20.4	17.8	5.5	14.5	4.4	1.8	1.8	1.3	.9	.9			1.4
M. 14	7.1	66	—	.3	.4	.6	1.1	5.3	1.4	31.1	24.9	8.5	17.0	2.2	2.5	.5	.3	1.7	1.0			1.2
M. 15	8.1	81	—	tr	.5	1.3	4.1	12.3	13.1	14.0	22.4	9.8	11.9	1.3	2.1	1.3	.8	1.8	.8			2.5
FJP.45	(Beach)	0	—	tr	.4	3.4	19.3	61.5	11.2	3.9	tr	—	—	—	—	—	—	—	—	—	—	—
S.J. 6	3.0	55	—	—	tr	.5	2.1	10.1	16.6	44.0	21.6	4.0	.9	—	—	—	—	—	—	—	—	—
S.J. 5	4.0	69	—	tr	.6	10.6	46.1	26.3	9.4	2.3	2.4	.9	.5	—	—	—	—	—	—	—	—	—
S.J. 4	5.0	79	—	tr	2.7	12.3	27.9	42.7	7.9	.9	2.1	1.5	1.1	—	—	—	—	—	—	—	—	—
S.J. 3	6.0	84	—	—	—	tr	.5	1.2	.5	.8	10.3	33.2	36.7	3.5	2.9	1.4	1.8	2.1	2.4			2.7
S.J. 2	7.0	93	—	—	—	tr	.2	.6	.3	.6	2.3	13.4	60.7	6.1	5.0	3.8	.9	.9	2.2			3.0
FJP.48	(Beach)	0	—	tr	tr	.7	10.7	65.5	19.2	3.1	.6	—	—	—	—	—	—	—	—	—	—	—
S.H. 7	1.5	50	tr	.2	1.4	5.3	12.2	33.5	30.3	12.5	3.6	.9	tr	—	—	—	—	—	—	—	—	—
S.H. 6	2.5	62	tr	tr	.4	2.7	13.4	45.1	22.4	12.4	2.6	.8	tr	—	—	—	—	—	—	—	—	—
S.H. 5	3.5	78	tr	.3	4.9	24.3	38.3	23.3	2.6	.5	2.8	1.2	.9	—	—	—	—	—	—	—	—	—
S.H. 4	4.6	102	—	—	tr	.2	.7	2.2	2.1	1.6	9.1	20.9	46.0	5.3	4.2	2.3	2.0	2.0	.4	.3		1.4
S.H. 3	5.6	118	—	—	tr	.2	.7	1.1	2.8	1.7	2.0	6.5	49.3	8.2	7.3	4.3	4.7	4.0	2.1	1.7		3.4
S.H. 2	6.6	134	—	—	tr	.5	1.7	4.4	3.1	2.5	1.2	1.4	31.5	13.3	12.5	6.8	6.5	6.2	3.6	2.4		2.4
S.H. 1	7.6	149	—	—	tr	.4	1.7	3.0	3.2	5.4	2.3	2.2	8.0	10.4	14.7	6.9	11.2	7.5	6.8	5.4		10.9
Sa. 0	(Beach)	0	—	—	tr	2.3	13.5	48.0	28.6	7.1	.1	—	—	—	—	—	—	—	—	—	—	—
Sa. 6	1.6	54	tr	tr	tr	.5	2.8	11.1	12.2	25.1	44.5	3.7	.4	—	—	—	—	—	—	—	—	—
Sa. 5	2.5	69	.5	.1	.3	6.2	20.6	37.7	20.8	7.3	4.9	.8	tr	—	—	—	—	—	—	—	—	—
Sa. 4	3.4	85	3.8	1.5	3.6	15.1	29.7	34.0	7.8	1.7	1.5	.5	.2	—	—	—	—	—	—	—	—	—
Sa. 3	4.4	108	—	—	tr	.4	1.5	3.2	3.5	2.6	21.8	20.9	20.2	2.4	3.7	.6	1.2	1.5	1.8	1.3		13.4
Sa. 2	5.3	133	—	—	tr	.2	1.3	2.5	3.5	2.2	4.6	14.6	45.2	7.4	8.0	2.8	—	2.8	1.2			3.7
Sa. 1	6.4	161	—	—	—	tr	1.3	2.4	2.5	2.4	2.0	3.8	29.9	13.8	11.0	4.6	5.5	10.1	10.7	—	—	
Sa. 15	15.0	288											21.7	3.3	8.4	7.8	11.8	14.0	14.7	9.3		9.0
Sa. 16	40.0	468											9.8	4.7	1.6	3.1	2.7	8.2	17.7	20.0	20.4	11.8
B.L. 0	(Beach)	0	—	—	—	1.5	12.0	47.4	26.0	12.9	tr	—	—	—	—	—	—	—	—	—	—	—
B.L. 1	5.2	138	—	—	—	.4	1.5	3.2	2.8	1.5	19.0	22.7	31.8	4.6	2.9	1.2	2.9	1.2	2.5	1.8	—	—
B.L. 2	10.3	260	—	—	—	.5	1.4	3.6	2.8	2.0	.7	.7	3.4	2.7	12.1	10.4	15.5	14.6	12.5	7.3		9.8

Legend: M. = Michigan City, S.J. = St. Joseph, S.H. = South Haven, Sa. = Saugatuck, B.L. = Black Lake.
* Remainder = amount below finest grade analyzed.

that sediments vary from coarse to fine directly as the distance from shore and depth of water increase. In the Michigan City series the variations in size of the sediment seem to bear some relation to the depth of water. Figure 2, Michigan City profile, shows that the coarser material occurs at the outer margin of a broad level area, at a depth which is lightly less than that of the finer sand nearer shore. However, the bottom profiles for the other localities show no such reversal of slope and hence no such correlation between size and depth of water.

Stetson found a similar situation on the continental shelf in the Atlantic Ocean from Cape Cod, Massachusetts, to Maryland. From a coarse sand near shore there was a change to a zone of fine sand mixed with silt, and then a marked coarsening of grade size at the break in slope of the shelf and for some distance farther down. This outer zone of coarse sand occurs at progressively greater depths, going northward.[22] Trask reported sand on the slope of the shelf in the northeastern side of Bering Sea, between an area of finer sediment on the shelf and one of finer sediment in the deep basin beyond the shelf-slope.[23] Similarly, Shepard noted the occurrence of coarse sediment at the outer margin of the continental shelf in many places throughout the world.[24]

[22] Stetson, H. C., *Woods Hole Oceanographic Inst. Rept.* for 1930–1932., pp. 48–49.

[23] Trask, P. D., *Origin and environment of source sediments of petroleum*, Huston: Gulf Publ. Co., pp. 134–135, 1932.

[24] Shepard, F. P., Sediments of the continental shelves, *Geol. Soc. America, Bull.*, vol., 43, pp. 1017–1039, 1932.

In Lake Michigan the coarsest sand is found at a depth of 51 feet at Michigan City, 69 feet at St. Joseph, 78 feet at South Haven and 84 feet at Saugatuck. Since the depth of the zone becomes greater to the northward, it could be explained as an old beach developed during a low water stage of Lake Michigan only if subsequent tilting down to the northward were assumed. Old beach lines which are above the present level of the lake are not warped in this area, hence this explanation for the submerged zone of coarse sand is rejected. The lack of adjustment of grade size to bottom profile may possibly show that the subaqueous profile is not in equilibrium with present conditions.

It seems likely that the boundary between the sand and the silt represents, roughly, a line along which bed rock approaches the lake bottom and outcrops occasionally. Leverett, following Lane, in the "Geologic Map of the Southern Peninsula of Michigan,"[25] places the surface of bed rock at a little less than 500 feet above sea level in the vicinity of St. Joseph, and slightly lower at South Haven and Saugatuck. The elevation above sea level of the boundary between sand and silt on the lake bottom is 497 feet at St. Joseph, 489 feet at South Haven, and 485 feet at Saugatuck. These figures agree rather well with the approximations of the elevation of bed rock for the same localities. The elevation of bed rock in northern Indiana in the vicinity of Michigan City, as shown by well records, is so variable that its posi-

[25] *U. S. Geol. Survey*, Mon. 53, Pl. II.

tion offshore cannot be approximated. However, during the sampling operations hard bottom was discovered with the clamshell snapper at the location of sample M. 14 (Fig. 2, Michigan City profile). In the first cast of the sampler it closed but was brought to the surface empty, while in the second cast, made after the boat had drifted a short distance westward, it was brought to the surface filled with silt. Hard bottom was not encountered in any of the other series, but the Lake Michigan Coast Chart No. 5[26] shows occasional occurrences of hard bottom, at points between the sampled lines, at depths and distances from shore which coincide with those of the sand-silt boundary.

The evidence of an outcropping of bed rock is augmented by the occurrence of a definite break in slope near the location of the hard point on the Michigan City profile, and by a similar break in slope in profiles drawn through the points marked "hard" on the chart. There is a suggestion of a break in slope near the sand-silt boundary on the Saugatuck profile.

Samples of silt, taken from 4 to 7 miles from shore, were found to contain a small amount of relatively coarse sand. This coarse material may have been carried into the silt zone during periods of storm.

Texture of the Sediments Near the Western Shore

I. The Area North of Chicago.— Two lines of samples were taken, one extending eastward from Kenosha, Wisconsin, about ten miles, the other eastward from Waukegan, Illinois, about six miles. The samples were spaced at half-mile intervals in both series, with the exception of the eastern end of the Kenosha line where the samples were taken at greater intervals as is shown in Figure 3 and in Tables III and IV.

The two profiles shown are quite different from each other; at Kenosha there is a very pronounced shelf while at Waukegan the bottom slopes down to the eastward with minor fluctuations only (Fig. 3). The shelf at Kenosha is nearly level, with an average depth of 50 feet, and extends to a distance of 4.2 miles from shore. It is backed on shore by wave-cut cliffs of glacial till, while sand occurs on the beach and in shallow water near shore. Gravel and till occur on the bottom from 0.8 mile to 2.5 miles from shore, while sand extends from the outer limit of the gravel-till zone to the edge of the shelf and down to the base of the slope. The till nearest shore is gray in color, but 1.8 miles from shore there is a stiff red clay containing some sand. This latter is apparently a southward extension of the "red till" of northeastern Wisconsin. A thin layer of reddish-colored sand found on top of the clay was apparently derived from the clay deposit, and represents a veneer shifted along the bottom during times of storm. East of the shelf, beyond the outer sand zone, a sandy silt occurs and extends as far east as the samples were taken.

There is no regular variation in the median diameter of the sediments on this profile. In a direction outward

[26] Index no. 75, *U. S. Lake Survey*, 1932.

TABLE III. *Mechanical Composition of Sand Samples of Kenosha Series*

Sample No.	Distance from shore in miles	Depth of water in feet	Per Cent by Weight in Each Grade Size. Grade Sizes in Millimeters.														
			1.397	.991	.701	.495	.417	.295	.208	.175	.147	.124	.104	.088	.074	.061	.000
3*	1.8	48	2.8	3.6	4.0	5.9	4.0	30.6	22.8	19.3		5.8			1.3		
5	2.9	51	13.5	1.4	3.3	4.9	3.8	31.8	19.9	8.2		8.3			4.8		
6	3.4	51	1.8	.5		.9	.7	3.9	6.3	36.7		39.8			9.2		
7	3.8	51		.5		.5		2.4	6.7	39.9		36.0		11.4		2.3	
8	4.3	60	27.5	.7	1.0	3.5	5.6	40.7	10.5	3.4		4.6			2.4		
9	4.8	96			1.3				4.6	29.3		33.7	24.2	6.6		.3	
10	5.3	108			1.2				1.5	9.7		17.5	19.6	24.5	7.3	18.4	
11	5.8	120			5.0				3.4	6.4	5.8	10.8	15.8	11.7	5.1	6.6	29.4
12	6.8	138			14.7				11.4	13.1	9.2	7.2	8.9	6.0	2.7	4.0	22.8
13	7.8	156			25.2				19.4	11.9	9.1	5.8	4.7	3.3	1.4	2.3	16.8
14	8.8	174			9.1			12.7	17.7	18.3	10.3	4.9	5.6	3.2	1.3	3.0	13.8
15	10.4	200			11.1			15.9	22.4	15.6	9.4	4.1	4.9	3.0	1.4	2.4	9.7

* Sand veneer overlying till.

TABLE IV. *Mechanical Composition of Sand Samples of Waukegan Series*

Sample No.	Distance from shore in miles	Depth of water in feet	Per Cent by Weight in Each Grade Size. Grade Sizes in Millimeters.										
			Over 2.00	2.00–1.40	1.40–1.00	1.00–.71	.71–.50	.50–.35	.35–.25	.25–.177	.177–.125	.125–.088	.088–.061	.061 .000
1	1.0	20	1.0	.3	.1	.1	.2	.5	1.0	4.5	24.8	44.1	18.1	5.0
2	1.5	37	—	—	tr	tr	.5	1.2	2.6	3.9	10.5	50.4	20.2	10.4
3	2.1	50	tr	tr	tr	.5	1.0	2.3	14.3	39.0	15.1	18.2	7.1	2.5
4	2.5	62	tr	tr	.4	.9	1.7	4.5	12.3	12.9	13.9	17.3	11.6	24.3
5	3.0	68	—	tr	tr	.4	1.0	3.2	10.7	9.2	5.7	20.8	22.5	26.6
6	3.5	72	—	—	tr	.2	1.1	5.9	29.7	44.8	13.3	1.5	1.2	2.0
7	4.0	82	—	tr	tr	.2	1.9	6.5	19.4	26.5	21.0	10.8	5.0	8.4
8	4.5	90	tr	tr	.5	.5	1.8	4.6	19.5	26.3	22.4	9.7	3.9	10.6
9	5.0	95	2.5	.1	1.2	2.4	5.1	11.4	31.5	24.4	15.0	3.9	1.0	1.3
10	5.5	103	tr	tr	tr	1.8	5.0	10.9	30.5	25.8	13.5	5.1	1.7	5.5
11	6.0	109	1.0	.2	.1	.9	3.1	8.8	26.3	22.6	15.1	6.1	3.5	12.2

from the edge of the till zone, the median diameter of the sand decreases from 0.325 mm. to 0.147 mm., then at the edge of the shelf increases to 0.380 mm. At the foot of the shelf-slope the median is 0.137; from there

of material in the silt range, as well as a few small pebbles. The occurrence of the coarsest sediment at the outer edge of the shelf is a phenomenon which has been discovered in a number of situations, as was pointed

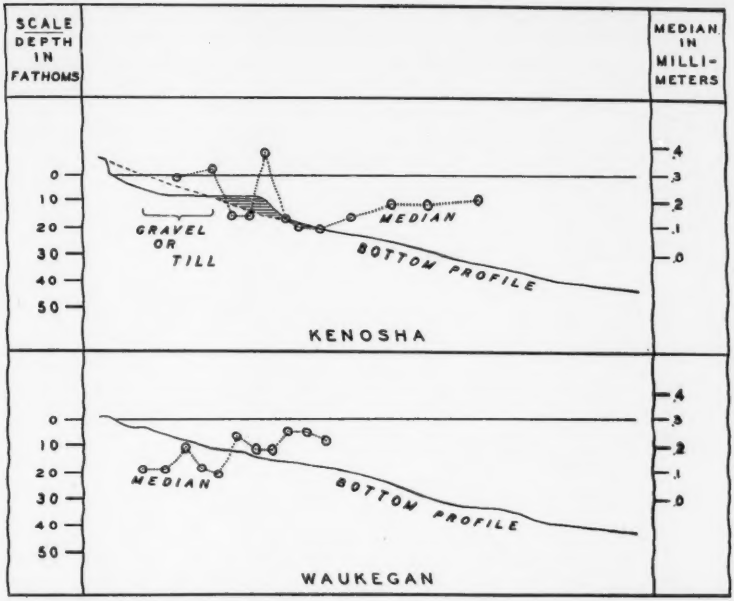

FIG. 3. Profiles drawn on the sampled lines, roughly perpendicular to the western shore. Graphs of the median values of the samples are superimposed. Length of profiles is 14.5 miles. *(See Tables III and IV.)*

eastward the size continues to decrease for about a mile, falling to 0.099 mm., but still farther east for an unknown reason the size increases until it reaches 0.205 mm., at a distance of 10.25 miles from shore. The last four samples in the series have been called a "sandy silt" because they are rather poorly sorted, containing, besides sand, a large amount

out above in the discussion of the sediments of the eastern shore. The explanation of this feature of the Kenosha profile is not known.

The inner half of the Kenosha shelf (Fig. 3), with a gravel-till bottom, is apparently an erosional feature, while the outer half, with a sand bottom, may be a depositional feature. If this be true Andrew's

calculation[27] of the total recession of the western shore of Lake Michigan is in error. Andrews found the average rate of recession of the western shore between Manitowoc and Evanston to be a little more than five feet per year, and the average width of the subaqueous terrace to be four miles. He assumed the terrace to be wholly wave-cut, and hence projected "the steepest part of the slope, just outside of the edge of the terrace, . . . upward till it met the surface of the water" and thus calculated the average total recession of the western shoreline to be 2.72 miles. Dividing this figure by the average annual rate of recession, he obtained 2720 years for the time required to cut the terrace. Johnson, as well as the present writer, believed the terrace to be partly cut and partly built.[28] Following Johnson's method, the slope of the deeper part of the Kenosha profile, beyond the terrace slope, was projected to the top of the cliff on shore; and it was found that the point where this projected line crossed the terrace lay between the till and sand zones (Fig. 3). The position of the old shore, at the point where the projected line reaches the surface of the water, lies about 0.85 miles east of the present shore at Kenosha. Dividing this distance by the rate of recession measured by Andrews, the figure of 855 years is obtained for the time required to form the terrace. Since the rate of recession is a diminishing rate, this figure should be reduced by some amount. The figure is obviously excessively low, and we must conclude that this method of calculating the length of a portion of post-glacial time is not a reliable one.

In contrast with the Kenosha profile, the Waukegan profile embraces a shore that is being aggraded rather than eroded. This is indicated by the presence of a barrier beach at the present shore at Waukegan, behind which lies swamp-land cut off from the lake, and by the fact that no glacial till or gravel is exposed on the bottom within a few miles of shore. The median diameters of the samples taken on the Waukegan line show no regular variation, and no close relation to depth of water or distance from shore. However, they do show a general tendency to become coarser with increasing depth and distance from shore (Fig. 3). A few small areas of rock bottom occur near shore on this profile, but apparently they have had little influence on its form.

II. The Chicago Area.—The area adjacent to Chicago was studied in greatest detail, because it was most accessible and because the bottom sediments are so irregularly distributed that a few lines of samples are not representative. Two large scale charts by the U. S. Lake Survey[29] show soundings spaced at an average interval of 1/4 mile over the whole area, down to a depth of 60 or 65 feet,

[27] Andrews, A. E., The North American lakes considered as chronometers of post-glacial time, *Chi. Acad. Science, Trans.*, vol. 2, p. 14, 1870.

[28] Johnson, D. W., *New England Acadian shoreline*, New York: John Wiley & Sons, p. 406, 1925.

[29] Chicago Lake Front no. 1, 1926, and Chicago Lake Front no. 2, 1926.

and frequent soundings in deeper water. The contours on the map shown in Figure 4 were drawn from these data. The bottom is shallow for a much greater distance from sand are the major types of bottom in the area extending from a few miles west of Michigan City, Indiana, to Evanston, Illinois (Fig. 1), and from the Chicago shoreline to 18 or

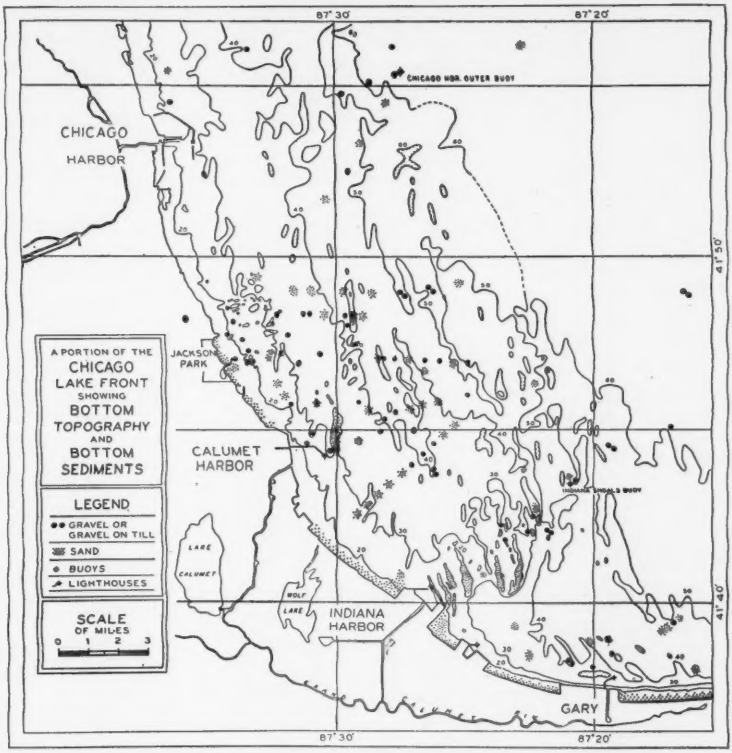

FIG. 4. Map showing the relation between topography and bottom material. The gravel concentrates, which lie on till, occur in the hollows and the sand occurs on the ridges. Contours drawn from the data of the base maps, U. S. Lake Survey charts Nos. 753 and 754, 1926.

shore than it is anywhere else in the southern half of Lake Michigan; the 60-foot contour is, on the average, ten miles from shore.

Gravel or gravel-veneered till and 20 miles northeastward. The deeper part of this area has not been investigated by the author, but the Lake Survey Chart No. 7 shows gravel at a depth of 132 feet, 19 miles

east-northeast from Chicago Harbor. Stimpson[30] describes the botton as "sandy or gravelly" at a distance of 18 miles from the Chicago shore. A fisherman who sets his nets in 100 to 120 feet of water east-northeast of Chicago, reports "clean yellow sand" and "gravel."[31] The author has collected gravel alone and gravel overlying till from the bottom in depths ranging from 20 to 60 feet.

The gravel is interpreted as a lag concentrate of the coarser constituents of glacial till, resulting from wave and current action on the bottom under present conditions. The gravel shows no evidence of having been subjected to stream or beach action (which might have occurred during a low-water stage of the lake); it is characteristically subangular in shape, and occasionally shows well-defined glacial striae. However the gravel concentrate was produced, it stands as evidence of present-day wave or current action on the bottom because there is no significant filling of the interstices by sand, silt or clay. The pebbles often occur directly on undisturbed till, unaccompanied by finer sediment. There are considerable quantities of material in suspension in the lake waters during times of storm, some of which may settle to the bottom in this region during calm weather, only to be picked up and carried somewhere else during succeeding storms. The finest constituents of the till must ultimately reach the deeper portions of the lake basin, while the sand which is derived from the till accumulates in bars and ridges, or is transported to the beach. The widespread occurrence of this gravel concentrate indicates considerable subaqueous erosion and with a large area of the lake bottom as a source of the sand, it is unnecessary to assume, as some writers have, that all of the sand which reaches the Indiana dunes has been transported southward along shore from the cliffs of the eastern and western shores.

Sand occurs on the bottom in this region about as frequently as does gravel. It is occasionally found as a thin veneer on glacial till, but the sand deposits are usually too thick to be penetrated by the sampling apparatus. The sand, where present, rarely exceeds a few feet in thickness. A notable exception is in the Indiana Shoals region, northeast of Indiana Harbor, Indiana, where several large bars occur, trending away from shore in a northerly direction. Some of these have been dredged extensively to obtain material for the construction of new land along the lakefront. The sand in the bars averaged 10 or 12 feet in thickness before dredging operations were begun. The depth of water over the bars was formerly from 13 to 20 feet, while the depth between them was from 25 to 30 feet. Gravel or till was found occasionally between the sand ridges before the latter were disturbed. An intensive survey of a comparatively small area adjacent to the property of the Inland Steel Company in which soundings and jet borings were made, shows that the topography of the

[30] *Op. cit.*, p. 404.
[31] Henderson, C., of Chicago, personal communication.

bottom bears no relation to the surface of the underlying till.[32]

A bar lying a half-mile east of the Calumet Harbor breakwater and trending in a northerly direction, also contains a considerable thickness of sand. The depth of water over the bar was recently 18 feet at the shallowest point, while on the lakeward side as well as between the bar and the breakwater the depth averaged 32 feet. This bar has been dredged two or three times because of its menace to shipping, but each time it has re-formed rapidly. Till bottom occurs in the deeper water between the bar and the breakwater.

The map (Fig. 4) shows a number of low ridges in the southern half of the region, some of which lie nearly parallel with the shore while others trend offshore at a small angle. Samples taken on several lines across the ridges show that the relation of sand on the ridge-crests and gravel or gravel-veneered till in the hollows apparently holds over the whole southern Chicago lakefront. These sand ridges do not partake of the nature of barrier bars, since they occur in deep water, often trend away from shore, and pitch toward deeper water. Except in the formation of barriers, the shallower portion of a bottom would be expected to suffer erosion, while the deeper portions should tend to be filled by the material derived from the shallower areas. The reverse conditions have been found. The general form of the bottom topography may have been inherited from a time when the lake surface was displaced considerably below its present level[33] and beach processes were active in a belt which progressed across the region as the water withdrew and again as it returned. However, the production or maintenance of a lag-gravel deposit on the till of the hollows at the present time, as well as the development of large ripple-marks on the sand areas,[34] indicates present-day action of considerable importance. The action may be that of currents developed by a set of conditions peculiar to the southwestern corner of the lake.

Laboratory analyses of the sand samples indicate no regular variation in size of the bottom sands (Tab. V). However, the samples were taken on lines transverse to the ridges; it may be that closely spaced samples taken parallel to the ridges would show a similarity or a regular variation. In some cases sand which was taken at depths greater than 50 feet, at distances of 8 to 12 miles from shore, was found to be coarser than sand taken from lesser depths.

Bed Rock of the Western Shore.—Rock shoals which are known to be reef structures of Niagaran limestone occur in the southern part of the Chicago area. The shallow outcrops

[32] The author is indebted to Mr. J. C. Alderman of the Great Lakes Dredge and Dock Co. for most of this information.

[33] There is evidence that lake level was once at least 45 feet lower than it is at present. Personal communication from G. H. Otto, Assistant to J. H. Bretz, Illinois State Geological Survey.

[34] Ripple marks with wave lengths of seven to fourteen inches have been observed with a device similar to that described by E. M. Kindle in Recent and fossil ripple-marks, *Can. Dept. Mines*, Mus. Bull. 25, p. 8, 1917.

TABLE V. *Mechanical Composition of Sand Samples from the Chicago Region*

Locality*	Sample No.	Distance from shore in miles	Depth of water in feet	Per Cent by Weight in Each Grade Size. Grade Sizes in Millimeters.									
				Over 1.40	1.40–1.00	1.00–.71	.71–.50	.50–.35	.35–.25	.25–.177	.177–.125	.125–.088	.088–.061	.061–.000
Jackson Park	J.P. 8	.8	22	3.0	.6	1.2	.6	8.7	29.1	42.5	10.7	1.4	1.0	.2
	J.P. 9	1.4	27	—	tr	.3	tr	7.5	40.0	36.9	12.0	.6	.9	1.2
	J.P. 22	3.0	37	—	.4	.4	1.0	2.3	10.9	34.6	40.2	6.7	1.7	.9
	J.P. 21	3.6	39	—	.2	.3	.7	3.0	13.2	19.9	43.8	13.3	3.4	1.6
	J.P. 20	4.5	42	—	.3	.2	.5	3.0	18.3	35.8	27.0	9.6	2.5	2.2
	J.P. 19	5.5	44	5.7	1.3	1.9	5.7	21.0	38.6	18.8	4.5	1.4	.5	.6
	J.P. 16	8.1	46	.6	.2	1.0	4.3	15.2	41.8	29.3	6.8	.3	.1	—
Calumet	C. 5	2.3	31	—	—	.4	1.1	2.4	7.4	12.6	42.8	25.1	5.5	2.2
Indiana** Harbor	I. 1	2.2	25?	—	—	—	tr	1.0	4.3	14.0	65.0	14.3	1.2	—
	I. 2	2.7	25?	—	.7	.8	.9	3.4	24.0	30.6	35.7	3.5	.3	—
	I. 3	3.0	23?	—	—	—	.3	1.4	3.5	14.5	53.8	13.6	9.4	2.9
	I. 4	3.3	24?	—	—	—	—	.3	.7	1.0	18.1	14.6	23.7	41.2
	I. 5	5.4	24	—	.3	.5	1.1	11.5	38.2	27.7	16.7	2.9	.5	.3
	I. 6	6.9	50	8.4	.4	1.2	tr	2.4	2.8	6.4	54.4	19.2	3.6	.8
	I. 7	8.4	54	1.4	tr	1.4	tr	26.4	45.0	10.4	12.9	2.0	.4	—
Gary	G. 4	1.0	34	—	—	—	—	tr	.8	.8	3.2	12.9	54.8	27.5
	G. 5	1.8	43	—	.3	.7	tr	3.3	19.5	33.7	37.6	3.3	.7	.4
	G. 9	2.4	45	—	—	—	—	tr	.6	3.0	33.7	23.4	29.5	9.6
	G. 13	2.7	48	—	—	—	—	tr	.5	2.0	36.7	39.2	19.3	2.0
Burn's Ditch	B.D. 1	.7	42	—	—	.5	tr	3.6	14.5	30.4	36.2	5.9	5.9	2.2
Downtown, Chicago	D. 2	12.5	105	—	—	.2	1.6	8.7	26.6	28.4	29.9	3.9	.2	.3

* These localities are shown on the map in Figure 7, in the text.
** Samples I. 1, I. 2, I. 3 and I. 4 were taken in the dredged area.

exhibit typical reef structure. Bretz regards the rock shoals between 39th and 55th streets as parts of one compound reef, and another group of shoals between 78th street and Calumet Harbor as parts of a second reef.[35] There are three other abruptly-rising areas of small extent lying from three to seven miles offshore, northeast or east-northeast of Calumet Harbor Lighthouse, which have not been investigated, but which may also be Niagaran reefs.

North of Chicago, a number of small rock shoals occur in relatively inaccessible depths,[36] but it is probable that they are also reef structures. Racine Reef, a large mass of rock located one mile southeast of the Racine, Wisconsin, harbor entrance, extends eastward for 1 1/4 miles and is 3/4 mile wide north and south. The least depth, near its center, is 7 1/2 feet.[37] Since the bedrock of the vicinity is the Racine Linestone, of Niagaran age, the material of Racine Reef may be assumed to be the same. The structure of the reef is apparently unknown.

Deep Water Sediments.—A soft gray clay was found in the center of the southern basin (Fig. 1). Nearly all of a sample taken 40 miles from shore on a line between Kenosha, Wisconsin, and South Haven, Michigan, was found to be finer than 1/16 mm. in diameter and 11.8 per cent was finer than 1/2000 mm. (Tab. II, sample Sa. 16.) A sample taken 15 miles offshore from Saugatuck (Sa. 15) is shown by Table II to be only slightly coarser. The material represented by these samples is believed to cover a large area in the deeper parts of the lake, because Stimpson reported a deposit of "blackish, impalpable mud," in 384 feet of water, 26 miles east of Racine, Wisconsin, and the Lake Survey chart shows "clay" over the whole of the southern basin, below 350 feet, and a similar deposit has been reported from the deeper portions of Lakes Superior,[38] Ontario,[39] and Erie.[40] Pegrum believes that all of the clay of Lake Erie was washed into the lake during glacial times.[41] Undoubtedly, much fine material was poured into the lakes from the melting glacial ice, but the author believes that this has been covered by a more recent deposit derived from the finer constituents of glacial drift, removed from the shore and bottom exposures by lacustrine erosion. The volume of till which has been removed by such processes is large, and must have supplied enough fine clay to form a deposit of considerable thickness on the bottom in the deeper basins of the lakes.

[35] Bretz, J. H., Geology of the Chicago Region, manuscript to be published by the *Ill. State Geol. Survey*. These shoals are described in *U. S. Lake Survey*, Bull., *Op. cit.*, pp. 185–186, and the chart, Chicago Lake Front no. 2, *Op. cit.*

[36] Locations given in the Lake Survey Bulletin, *Op. cit.* pp. 182–183.

[37] Ibid., p. 179.

[38] Smith, S. I., Dredging in Lake Superior under the direction of the U. S. Lake Survey, *Am. Jour. Sci.* (3), vol. 2, p. 374, 1871.

[39] Kindle, E. M., *Op. cit.*, pp. 45–46. Nicholson, H. A., Preliminary report on dredgings in Lake Ontario, *Annals Nat. Hist.* vol. 10, 4th. ser., pp. 276–284, 1872.

[40] Pegrum, R. H., Preliminary report on the cooperative survey of Lake Erie, *Buffalo Soc. Nat. Sci.*, Bull, vol. 14, pp. 20–24, 1929.

[41] Ibid., p. 22.

The only distinguishable organic remains found in this clay in Lake Michigan were a few *Sporangites*, Devonian plant spores, redeposited from the original rock or from an intermediate resting place in glacial till.[42] Stratification was not observed in the core samples of the clay, but the cores were not sectioned until after they had dried. Possibly the fresh samples would have shown some structure since in drying they shrank to about half their original volume.

A sample of reddish-brown, stiff, sandy clay taken at a distance of 22 miles from shore, east and a little north of Waukegan, Illinois (Fig. 1), is apparently from the same deposit as the "reddish or brownish, sandy mud" found by Stimpson in 240 to 360 feet of water, 12 to 22 miles east of Racine, Wisconsin.[43] Further investigation, between the two localities, may show that this material forms a more or less continuous zone, but for the present this area on the map is left blank. The composition and consistency of the deposit suggest that it is not a recent sediment. It seems to be related to the "red till" which occurs on the western shore of the lake as far south as Cudahy, a few miles south of Milwaukee, Wisconsin. The "red till" is considered to be a glacial outwash deposit, formed during a period of retreat of the Glacial ice which once occupied the basin, and subsequently overridden and incorporated into a moraine during a period of readvance of the ice.[44] If the bottom materials in question do represent glacial deposits, either undisturbed red outwash or ice-pushed morainal material, they indicate that the western side of the deep central basin is not accumulating present-day lake sediments.

[42] Hough, J. L., Redeposition of microscopic Devonian plant fossils, *Jour. Geology*, vol. 42, pp. 646–648, 1934.

[43] Stimpson, W., *Op. cit.*

SUMMARY

The results of this study may be summarized as follows:

1. The beach sand samples of the western shore of the southern basin of Lake Michigan, with one exception, are definitely finer than those of the eastern shore.

2. The beach sands of the western shore show a decrease in median diameter from Highwood, Illinois, to Rogers Park, Illinois, and a slight increase from Rogers Park to Miller, Indiana. A few miles east of Miller the median becomes much greater; but on the eastern shore the median tends to decrease in a direction from south to north, between Waverly Beach, Indiana, and Macatawa (Black Lake), Michigan.

This northward decrease in size on both shores does not harmonize with evidence of southward littoral drift, if it is assumed that a decrease of size in the direction of transport always occurs.

3. The bottom sediments of the eastern half of the basin are sand, silt and clay. The sand is usually found within 3 or 4 miles of shore, the silt

[44] Martin, L., The physical geography of Wisconsin, *Wis. Geol. & Nat. Hist. Survey*, Bull. 36, pp. 252–253, 1916. Alden, W. C., *U. S. Geol. Survey*, Prof. Paper 34, p. 69, 1904.

occurs beyond the sand, and the clay occurs in the deeper parts of the lake, generally below 250 feet.

4. Within the sand zone which parallels the eastern side of the lake, the average size of the sediment first decreases with increasing distance from shore, then increases markedly becoming even greater than that of the beach material in most cases. The depth of the zone of coarse sand becomes greater to the northward.

The lack of continuous outward decrease in size does not conform to the principle that sediments vary from coarse to fine directly as the distance from shore and depth of water increase. This is taken as an indication that the bottom profile is not in adjustment with present conditions, but is more gently sloping than the theoretical profile of equilibrium.

5. Notations of "hard bottom" along the line of the sand-silt boundary, and coincidences between the elevations of the latter and the elevations of bed rock under the adjacent shore, are evidence that bed rock approaches the bottom and outcrops occasionally along this line.

6. In the western side of the southern basin of Lake Michigan there is an assemblage of sediments which is different from that of the eastern side. The most important difference is that glacial till, with a veneer of gravel, is of frequent occurrence.

7. At Kenosha, Wisconsin, on the western shore, the bottom profile shows a pronounced shelf about four miles in width, with glacial till or gravel on its inshore half and sand on the outer half. This shelf is interpreted as a cut- and built-feature.

8. Within the sand zone on the outer half of the Kenosha shelf the median diameter increases with the depth and distance from shore, the coarsest sediment occurring at the outer edge of the shelf.

The finest sediment of the series occurs near the foot of the shelf-slope, from which place the median diameters again increase as the depth of water and distance from shore increase, going eastward as far as the samples were taken.

9. At Waukegan, Illinois, on the western shore, there is no shelf; only a fairly regular slope down to the east, on which no till bottom was found. The shore is here formed by a barrier beach behind which lies swamp land; the inshore end, at least, of the profile, therefore originally had a slope more gentle than that of the profile of equilibrium. The median diameter of the sand on the bottom shows a small, irregular, but definite increase to the eastward, as the depth of water and distance from shore increase.

10. In the area which extends from a few miles west of Michigan City, Indiana, to Evanston, Illinois, and from the Chicago shore to 18 or 20 miles northeastward, sand bottom alternates with gravel-covered till bottom. The depth increases more gradually in this area than in any of the others studied; the 20 fathom contour lies 20 miles from the western Indiana shore.

11. The gravel veneer in the western part of the lake is interpreted as

a lag concentrate of the coarser constituents of glacial till, produced by wave and current action on the bottom.

12. The median diameter of the sand which is associated with the gravel in the Chicago region bears no relationship to depth of water or distance from shore, nor does it show any regular variation from sample to sample.

13. There is a relationship between topography and type of sediment in the Chicago region, however, because the sand is found on the numerous low broad ridges, and the gravel-till bottom occurs in the hollows between the ridges. The explanation for such an unusual distribution of material may be found to involve bottom currents generated by wind drift of surface water.

14. The soft gray or bluish-gray clay of the deeper part of the southern basin of Lake Michigan is believed to be forming at the present time, its substance being derived mainly from the clay fraction of glacial till which is undergoing erosion on the bottom in shallower water and along the shores of the lake. No stratification was observed in the dried core samples of the clay.

15. A stiff reddish-brown, sandy clay found at a distance of 22 miles from shore east of Waukegan is tentatively correlated with a "reddish or brownish, sandy mud" found by Stimpson between 12 and 22 miles from shore east of Racine, Wisconsin. The clays of both areas may be related to the "red till" moraine of northeastern Wisconsin, which occurs on the Wisconsin shore as far south as Cudahy. If they are of glacial origin, they indicate that the western side of the deep central basin is not accumulating present-day sediments.

The author is indebted to Dr. F. J. Pettijohn for his interest and help throughout this work.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 5, NO. 2, PP. 81–92, FIGS. 1–12, TABLES I–III, AUGUST, 1935

STRUCTURE AND ORIGIN OF THE PHOSPHORITES OF THE U.S.S.R.*

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ABSTRACT

Among the sandy phosphorites of the U.S.S.R., series of genetic structures have been discovered which decipher to a certain extent the mechanics of the accumulation of phosphates.

These structures have been observed in all the phosphorites examined from the various geologic systems and from different parts of the country. The degree of facility of phosphatization was ascertained for different intervals. The chemical constitution of the phosphorites examined has no resemblance whatever with known phosphate minerals.

CLASSIFICATION OF PHOSPHORITE NODULES

Engelhardt[1] discriminated in 1898 between three types of phosphorite nodules: the clay, the quartz-sandy, and the glauconite-sandy type. These forms were differentiated on the basis of the residue left after treatment in weak acids; the clay type leaving a clay residue, the quartz-sandy type a quartz-sandy residue and glauconite-sandy type a glauconite-sand residue. The classification of phosphorites on the basis of unsoluble residue corresponds to the chemical character: the clay type contains from 25 to 35 per cent P_2O_5, the quartz-sandy type from 10 to 20 per cent, and the glauconite-sandy type from 18 to 25 per cent. The phosphate of the clay type is amorphous and that of the sandy type is amorphous and radial or radial-ray phosphate.

* Published by permission of the Academician E. W. Brizke. (Director of the Scientific Institute of Fertilizers. Moscow.)

GEOLOGICAL DISTRIBUTION

The sandy phosphorites in the U.S.S.R. are found in the Cambrian Obolus sandstones in the vicinity of Leningrad, the Jurassic and Cretaceous strata of Middle and South Russia and the Paleogene layers in the south and southeast of Russia. Most of sandy phosphorites of U.S.S.R. are in the Cenomanian and Santonian of the Upper Cretaceous.

The Cenomanian phosphorites are almost exclusively confined to the basin of the Dnieper river (the deposits of Briansko-Kurski district) and have been known in the literature of the subject for a considerable time under the name of Kurski Samorod. They occur in two or three layers in quartz sands (Fig. 1). The lower phosphorite layer consists of more or less rounded phosphorite nodules from 1 to 5 centimeters in diameter. Two principal generations of these phosphorites may be distinguished: (1) phosphorite pebbles of the clay type with a considerable

quantity of phosphatized radiolaria (Fig. 5) and diatoms, and (2) slightly rounded nodules of sandy phosphorite (Fig. 6). Phosphorites of the first generation are scarce.

The upper phosphorite layer consist partly of rough and partly of slightly rounded phosphorite nodules. The nodules are often cemented into a phosphorite plate. The top of the plate is knobby, and is coated with a thin lustrous crust (glaze). The thickness of the glaze seldom exceeds one millimeter and ranges usually between 0.05–0.02 millimeters. Under the glaze the plate consists of compact sandy phosphorite from 0.05 to 0.3 meters thick. Beneath this appear large pores filled with sand which increase downward in size and number, and further downward the plate becomes separate rough phosphorite nodules ranging from 5 to 10 centimeters in diameter. The layer has thickness ranging from 0.10 to 0.5 meters. Such a phosphorite plate may extend for scores and even hundreds of kilometers, but it often changes into rough phosphorite nodules.

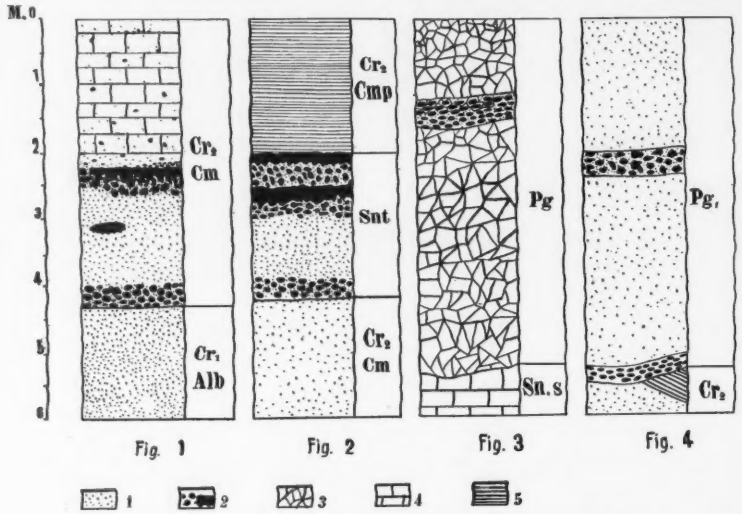

FIG. 1–4. Sections of the strata containing phosphate. Sand (1), phosphorite (2), gaize (3), chalk (4), clay (5).

It is easy to observe in a polished cut of phosphorite plate that it consists of phosphorite nodules, in some cases mixed with phosphorite pebbles cemented with phosphate.

Quartz sand with a mixture of calcareous material (powdered calcite-drewit), *Inoceramus* prisms, fragments of pelecypod shells, and tests of foraminifera overlies the phosphorite plate. This sand passes upward into sandy chalk. Sandy

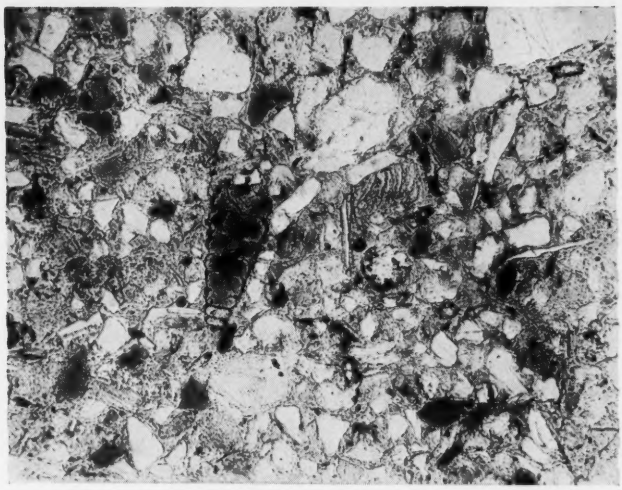

FIG. 5. Phosphorite with Radiolaria, Cenomanian, Kursk.

phosphorite nodules with lustrous surfaces are scattered throughout the sand and the chalk. The sand is less than 0.5 meters thick and the thickness of the sandy chalk ranges from 1.5 to 2 meters. In the upper part of the phosphorite plate and in the sand which covers it there may

FIG. 6. Phosphorite nodules with phosphatized sponges (1–6), Kursk.

be found abundant Cenomanian fossils among which are *Actinocamax primus* Arkh., *Pecten asper* Lam., *P. orbicularis* Sow., *Plicatula inflata* Sow., *Exogyra conica* Sow., *E. halitidea* Sow., *Terebratula dutempleana* d'Orb., *T. carnea* Sow., *Rhynchonella nuciformis* Sow., *Jerea kurskensis* Hofm., *Cribrospongia* sp., and teeth and bones of reptiles and fishes. Many oysters adhering to the phosphorite nodules were found and also phosphorite fillings are present in some oysters and also other pelecypods. It may be concluded that the above listed bottom fauna existed at the time the phosphorite was formed. It is obvious that the sea in which the phosphate was settling possessed normal ocean salinity, and that there was sufficient oxygen near its bottom for support of a benthonic fauna, as previously noted by A. D. Archangelsky.[2] The thickness of the valves of molluscs ranges from 0.5 to 5 millimeters, suggesting that the agitation of the waters near the sea bottom was strong. The thickness of Cenomanian deposits ranges ordinarily from 3 to 5 meters and rarely attains 10 meters.

At Aktubnisk the phosphorites are present in one to three layers of nodules and a phosphorite plate (Fig. 2), but in this case the phosphorites belong to the Santonian.

The Krolevetz phosphorites (Ukraine) have the appearance of black pebbles from 1 to 4 centimeters in diameter. These rest on the eroded surface of the chalk of the *Belemnitella mucronata* zone (Cr. 2), and are cemented with gaize (Siliceous earth. Fig. 3). Among the pebbles may be found rounded phosphorite pelecypod casts and phosphatized sponges. The Krolevetz phosphorites may be assigned to the Paleocene.

The Kazalinsk sandy phosphorites are in the Paleocene and occur among quartz sands (Fig. 4). The lower stratum consists of phosphorite pebbles of the clay type, and of coarsely rounded phosphorite nodules of the sandy type. The upper stratum consists of rough nodules of the sandy type.

MICROSCOPIC CHARACTERISTICS

Thin sections show that the phosphorites usually consist of quartz and glauconite sand cemented with phosphate. The quartz grains are usually well rounded. The glauconite is mostly granular and is rarely in finely divided form. The quantities of quartz, glauconite, and phosphate are shown in Table I.

Only averages are shown. The phosphate contents were obtained by multiplying the percentage of P_2O_5 by the coefficient 2.82 (see further). The column of "others" includes the feldspars, micas, accessory and clay minerals, free carbonates, hydrated silica, sulphates, sulphides, iron, titanium and manganese oxides, organic substance, and combined water.

The quantity of feldspars and accessory minerals in all the phosphorites examined is very small, rarely exceeding one per cent. The following minerals have been found: orthoclase, microcline, plagioclase, magnetite, rutile, garnet, epidote, hornblende, zircon, tourmaline, and kyanite.

TABLE I. *Mineral Composition of Phosphorite Nodules*

Locality	Stratum	Percentage contents of				Average size of grains-mm.	
		Quartz	Glauconite	Phosphate	Others	Quartz	Glauconite
Kursk	Upper	52.0	1.5	41.1	5.4	0.25	0.10
Kursk	Lower	38.0	5.0	48.5	8.5	0.10	0.10
Aktubinsk	—	38.0	1.8	51.1	9.1	0.15	0.10
Krolevetz	—	29.0	7.0	52.7	11.3	0.08	0.08
Kazalinsk	Upper	53.0	1.0	34.0	12.0	0.35	0.10
Kazalinsk	Lower	34.0	1.0	53.9	11.1	0.20	0.10

Calcite has been microscopically detected only in the upper part of the upper stratum of the Kursk and Aktubinsk phosphorites, the calcite in Kursk phosphorites resultive from incomplete phosphatization of chalk, whereas in the Aktubinsk phosphorites, calcite is secondary, as it fills crevices in the phosphorite.

The quantities of glauconite contained in the phosphorite nodules and the surrounding matrix are nearly the same, indicating that the formation of glauconite had been completed by the time phosphorite cementation began. In addition there were found bones and teeth of reptiles and fishes, colites, phosphatized siliceous sponges, radiolaria, diatoms, wood and chalk.

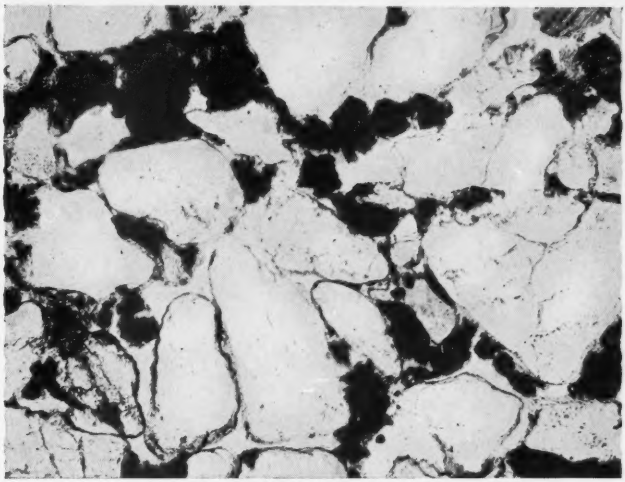

FIG. 7. Colloidal cluster-shaped phosphate (black) separating quartz grains (×70), Kursk.

The following varieties and stages of consolidation of phosphates in phosphorite nodules have been determined:

1. Amorphous cluster-shaped phosphate—1st stage of consolidation:

2. Radial phosphate geodes—2nd stage of consolidation;

3. Light microcrystalline phosphate—3rd stage of consolidation.

Amorphous Cluster-Shaped Phosphate under the microscope shows grains and clusters enclosed in pores between grains of sand (Fig. 7). In some parts of the thin section amorphous phosphate forms a compact cemented mass changing into cluster-shaped phosphate only on the margins of the mass. The phosphate is grey to black, depending on the content of organic matter. It also contains a few specks of quartz, glauconite, particles of clay, and, in some cases, irregular bodies of pyrite. Phosphorite nodules consisting exclusively of cluster-shaped phosphate are very scarce, accessory phosphate geodes being nearly always present.

Radial Phosphate Geodes in the phosphorite nodules are developed as crusts coating the walls of minute pores left by the consolidation of cluster-shaped phosphate (Fig. 8). The thickness of the crust ranges between 0.01 and 0.03 millimeters. This crust is composed of phosphate crystals radially directed towards the plane of accumulation. In some cases a crust has concentric lamination in alternating light and dark bands. J. V. Samoiloff[3] in 1912 described radial phosphorite crusts in the Volga phosphorites as "an inflow mass on the walls of cavities and crusts around various mineral grains."

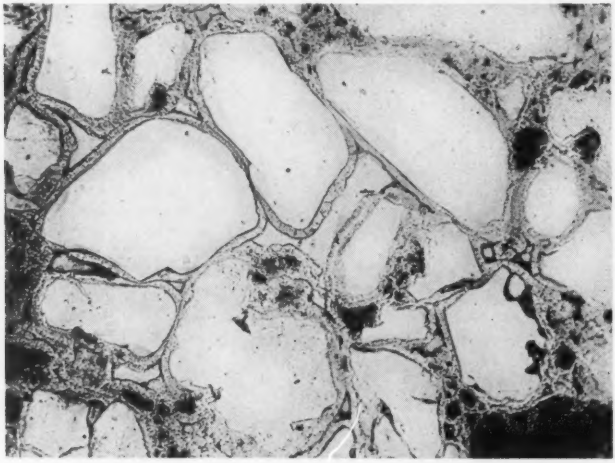

FIG. 8. Walls of phosphorite pores coated with crusts of phosphate with radiate structure (×70), Kursk.

Light Microcrystalline Phosphate fills the pores left by the consolida-

tion of cluster-shaped phosphate and of radial phosphate geodes (Fig. 9). This phosphate is very scarce.

Phosphatized Chalk in nodules was observed among the phosphates of Kursk, Aktubinsk, and Kazalinsk. In the Kursk phosphates such nodules occur in the upper part of the upper phosphorite stratum, and in the sand and sandy chalk covering the phosphorite. Some of the nodules are quite free from calcite, whereas others contain large quantities. The latter have a structure consisting of an outer layer composed of amorphous phosphate, with phosphatized tests of *Globigerina*, and prisms of the shells of *Inoceramus;* a middle layer containing phosphatized tests of *Globigerina* and calcite prisms of the shells of *Inoceramus;* an inner layer or nucleus of phosphorites composed of unaltered tests of *Globigerina;* unaltered prisms of shells of *Inoceramus*, amorphous phosphate and a mixture of drewite. These layers grade into each other. Thus the phosphatization of chalk is quite evidently taking place from the outer layer inwards. Fine-grained calcite crystals became phosphatized most easily, wheras the relatively coarse calcite crystals of the prisms of the shells of *Inoceramus* were the last to phosphatize.

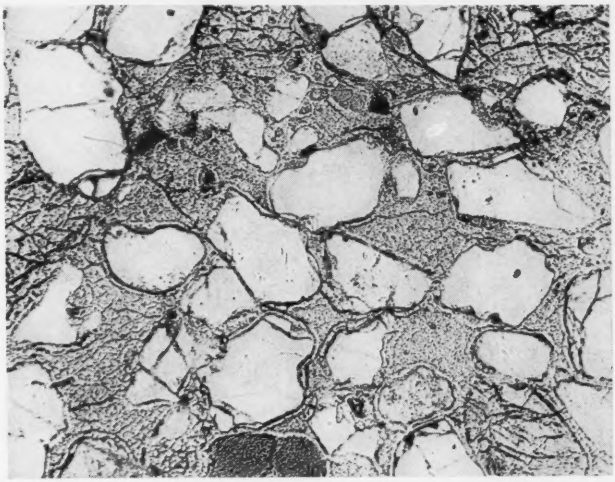

FIG. 9. White micrystalline phosphate (3rd stage of consolidation) filling spaces between grains of quartz (×70), Kursk.

It is interesting to note that *Cyprina* shells are rarely preserved in original composition but are generally changed to phosphate. The original material of these shells is aragonite and it is evident that aragonite is easily replaced by phosphate. The calcite of oysters, brachiopods, and other animals are

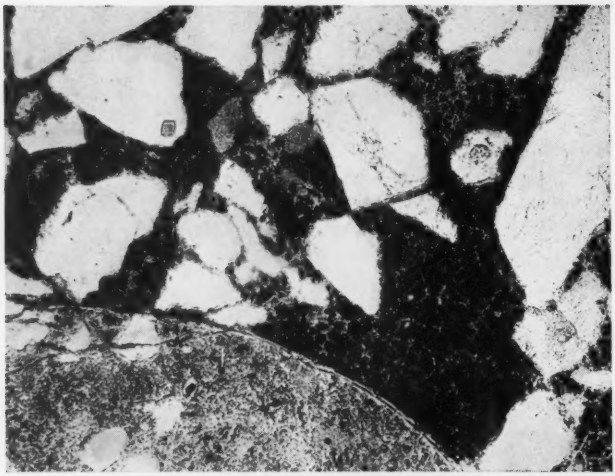

FIG. 10. Network structure of phosphate characteristic of phosphatized chalk. There is a part of a phosphatized pebble of the clay type at the bottom (×70), Kursk.

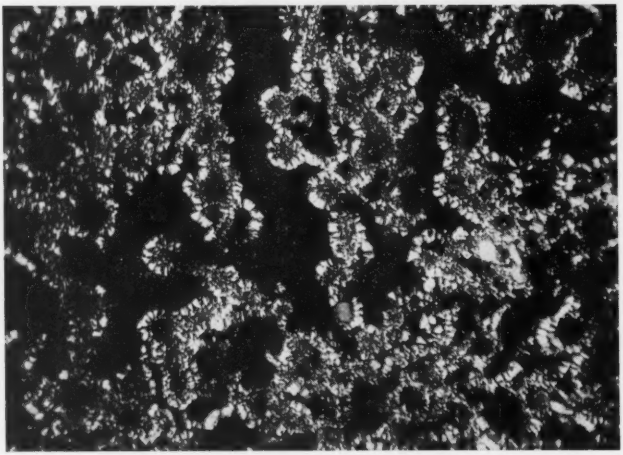

FIG. 11. Phosphatized sponge. Fine-grained phosphate replaced siliceous spicules and filled hollows in the spicules. Crystals of radial phosphate are on the surfaces of the spicules (×100), crossed nicols, Briansk.

usually not replaced by phosphate but are preserved in original form.

Phosphatized chalk nearly always shows a network structure (Fig. 10). In reflected light the phosphate within the spaces of the network is

not gray, as in transmitted light (Fig. 10), but white and the net fibres are gray. As I have never noticed a similar structure in phosphates of other origin, I am inclined to consider it as one of the peculiarities of phosphatized chalk.

Phosphatised Wood, Radiolaria, and Diatoms consist of pure fine-grained crystalline phosphate, preserving all the details of the organic structure. The phosphatization of sponges proceeded in a different way. One may see in phosphorite layers abundant hexactinellid sponges of which the hydrated silica of the spicules was replaced by microcrystalline phosphate (Fig. 11).* When found apart from sponges, the spicules have naturally no radial phosphate on them.

Fragments of Bones and Teeth are of ordinary occurrence in phosphorite formations as the conditions are most favorable for the preservation of the phosphate of the bone in the phosphorites. Consequently, it seems hazardous to make any genetic deductions on the basis of the bones abounding in the phosphorites.

Phosphate Oolites are found in groups among sandy phosphorites, but occurrences are very rare. These oolites are gray in color and spherical or ellipsoidal in shape. Concentric or radial structures have not been observed and these oolites are considered to represent phosphatized coprolites. The work of N. V. Moore[4] shows faecal grains of recent worms, of the species of *Syndosmia* and *Maldanid-Rhodine*, differing in no way whatever in shape and size from the oolites of the phosphorites in the Rockies, North Africa, and U.S.S.R. Moreover in the Rocky Mountains,

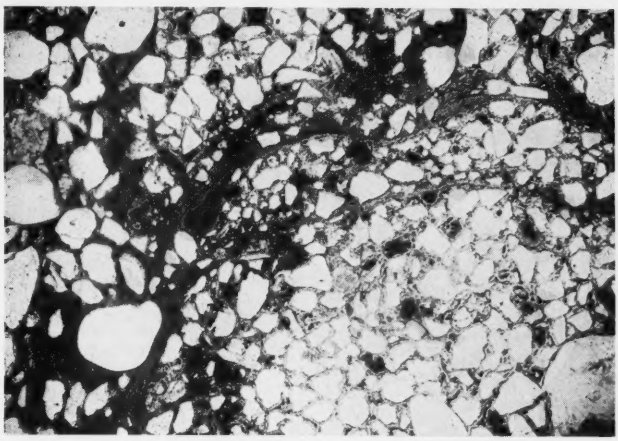

FIG. 12. Three layers of phosphorite growth, divided by bands of amorphous phosphate (×20), Kursk.

* The surfaces of spicules inside the sponges are covered by crusts of geodal phosphates.

TABLE II. *Chemical Analyses of Phosphorites*

Radicals	1	2	3	4	5	6	7	8	9	10
SiO_2	36.65	47.01	48.03	33.90	37.10	36.04	45.43	30.89	36.30	34.10
Al_2O_3	1.02	0.70	1.65	2.10	1.49	1.48	0.03	1.43	—	2.50
Fe_2O_3	1.77	2.37	1.85	2.05	2.96	2.79	2.92	3.29	—	2.89
FeS_2	0.05	0.00	0.00	0.00	0.14	0.08	0.29	0.00	—	0.28
TiO_2	0.16	0.11	0.09	0.08	0.08	0.08	0.11	0.05	—	0.00
MnO	0.04	0.05	0.04	0.04	0.02	0.01	0.02	0.03	—	0.03
CaO	29.43	24.01	23.86	29.82	28.31	29.32	26.21	31.45	28.04	28.91
MgO	0.50	0.42	0.34	0.62	0.06	0.06	0.61	0.62	—	0.41
Na_2O	1.01	0.70	0.60	0.71	0.57	0.58	0.34	0.72	—	0.72
K_2O	0.47	0.37	0.53	0.68	0.50	0.47	0.16	0.38	—	0.51
P_2O_5	17.14	15.61	15.25	19.99	18.72	18.75	16.05	19.10	19.10	18.69
CO_2	5.19	2.73	2.94	3.88	3.88	3.85	3.12	4.07	3.33	3.50
F	2.08	1.88	1.82	2.06	2.14	2.11	1.87	2.52	1.92	1.99
Carbon	0.58	0.48	0.62	0.66	0.25	0.42	0.45	0.56	—	0.67
SO_3	1.48	1.20	1.11	1.06	1.31	1.23	0.86	1.37	—	1.07
H_2O plus organic substance	3.14	2.60	2.96	3.27	3.13	3.26	2.78	2.86	—	5.14
O corresponding to F	0.88	0.79	0.76	0.86	0.90	0.89	0.79	1.06	—	0.83
Total	99.25	98.97	100.31	99.40	99.51	99.22	99.01	97.72	—	99.91

1. Upper phosphorite stratum, Cenomanian—Briansk, Orlovski, Dvoriki.
2. Middle phosphorite stratum, Cenomanian—Briansk, Bolshoye Polpino, average specimen of phosphorite nodules >20 mm. in diameter.
3. Ditto—Phosphorite nodules >4 mm. in diameter.
4. Lower phosphorite stratum, Cenomanian—Briansk, Bolshoye Polpino, average specimen of phosphorite nodules >4 mm. in diameter.
5. Top layer of lower phosphorite stratum—Briansk, Podboojye, average specimen of phosphorite nodules >4 mm. in diameter.
6. Ditto—lower layer.
7. Upper phosphorite stratum, Cenomanian—Kursk, Shchigri, average specimen of phosphorite nodules >4 mm. in diameter.
8. Average specimen of phosphorite nodules >20 mm. in diameter, Santonian, Aktubinsk, Kandagatch.
9. Paleogene phosphorite nodules, average specimen, class 1st—4 mm. in diameter. Lower phosphorite stratum, Kazalinsk.
10. Paleogene phosphorite nodules—Ukraine, Krolevetz.

phosphorites some coprolites had been covered by the concentrically-laminated envelop of phosphate and there are also true concentrically-laminated oolites of phosphate.

Phosphorite Pebbles differ from most other pebbles in that they may continue growth after burial. These pebbles show from seven to ten concentric layers of phosphorite growth. The layers of growth differ from each other in the character of the phosphates as well as in the character and quantity of enclosed minerals. In some cases the layers show a great similarity. Between any two layers there is usually a band of amorphous phosphate. Figure 12 shows two such bands dividing layers of growth. It was found that the lustrous crust so often observed on the phosphorite nodules is exactly similar to the phosphate band separating the layers of growth. The glaze of the phosphorite plate represents a strongly developed lustrous crust, or a sries of

TABLE III. *Recalculated Chemical Composition of Phosphate from Phosphorite Nodules*
(Quantity of phosphate taken as per 100 per cent)

Radicals	2	3	4	5	6	7	8	9	10
$Ca_3(PO_4)_2$..	77.20	76.17	76.99	75.56	75.77	76.23	74.29	78.20	77.20
$CaCO_3$....	14.07	15.28	15.56	16.31	16.20	15.43	16.49	14.33	15.07
CaF_2.....	8.73	8.55	7.45	8.13	8.03	8.34	9.22	7.47	7.73

such crusts stratified on top of each other. The formation of the phosphorite nodule, i.e., the consolidation of the phosphates of the first and second stages, evidently was totally completed by the time the following phase of growth began. The lustrous crust represents a pause in the deposition of phosphorite.

CHEMICAL CHARACTERISTICS

The phosphate content in the sandy phosphorites is not large and ranges from 15 to 19 per cent estimated as P_2O_5 (Table II).

The chemical analyses were made by S. N. Rozanoff in the Laboratory of the Scientific Institute of Fertilizers in Moscow. Microscopical examination of the analyzed samples showed no mixture of fluorite and iron and aluminium phosphates. Calcite was found in sample No. 1 and in very small quantities in samples Nos. 8 and 9. It is clear that almost all CO_2 and F in samples Nos. 2–10 are bound in the phosphate molecule. If the phosphate part of the phosphorite nodule is taken as 100 per cent, the following proportions result: (Table III).

It can be seen that these proportions are fairly stable and fall into the formula $5Ca_3(PO_4)_2\ 3CaCO_3 2CaF_2$. As the connection between CO_2 and F and phosphate is not yet clear, this formula can not be considered as finally established. Nevertheless it has been used in Table I for calculating the quantity of phosphate.

W. N. Tchirvinsky,[5] A. D. Archangelsky,[6] and, later, M. P. Fiveg and S. N. Rozanoff[7] distinguished two phosphate minerals in the phosphorite nodules of the U.S.S.R: Kurskite ($2Ca_3(PO_4)_2\ CaCO_3\ CaF_2$), an amorphous phosphate, and staffelite, ($3Ca_3(PO_4)_2\ CaCO_3\ CaF_2$) an anisotropic phosphate of radial structure. The cited chemical analyses do not correspond to kurskite or to staffelite or to a mixture of these two minerals. A. Rogers[8] united a series of phosphates which had been considered separate minerals under the name of collophane with composition of $3Ca_3(PO_4)_2 \cdot nCa(CO_3, F_2, SO_4, O) \cdot x(H_2O)$, but the contents of CO_2 and F in the phosphates under discussion are greater than in collophane or in the phosphates studied by S. Hendricks, M. E. Jeferson and V. M. Moseley.[9] The works of S. N. Rozanoff, not yet published, reveal a much greater complication in the character of connection between CO_2 and F with phosphate. As long as this connection has not been made thoroughly clear, a formula of phosphate can not be deducted from the gross analyses cited in these pages.

According to the definition of V. P.

Russakoff[10] the Cenomanian phosphorites from Briansk contain from 20 to 25.10^{-10} per cent radium, and about 20.10^{-5} per cent thorium, whereas the quantity of radium in the surrounding rocks is 5–6 times smaller. Evidently, these phosphorites by their radio activity are near to recent sea sediments.[11]

SUMMARY

The sandy phosphorite nodules from different parts of the Soviet Union and of various geological ages have a series of common features of development. They were formed in shallow basins with normal ocean salinity. The cementation of phosphorite nodules proceeded in two principal stages: (1) the formation of colloidal phosphate, and (2) the growth of radial phosphate crusts on the walls of minute pores in the middle of the nodules. The formation of glauconite was completed before the beginning of cementation of the phosphorite. The growth of phosphorite nodules occurred at intervals. These intervals were sometimes accompanied by erosion of phosphorite layer, and by accumulation of heavy minerals. Aragonite is quickest to phosphatize; it is followed by drewite and foraminiferal skeletons, and the prisms of shells of *Inoceramus* are the slowest to phosphatize. Phosphorite nodules occurring in the sandy chalk were formed by phosphatization of chalk. The replacement of calcite by phosphate proceeded from the surface of the nodule towards its centre.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 5, NO. 2, PP. 93–95, FIG. 1, TABLE I,
AUGUST, 1935

A TIME CHART FOR MECHANICAL ANALYSES BY THE PIPETTE METHOD

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ABSTRACT

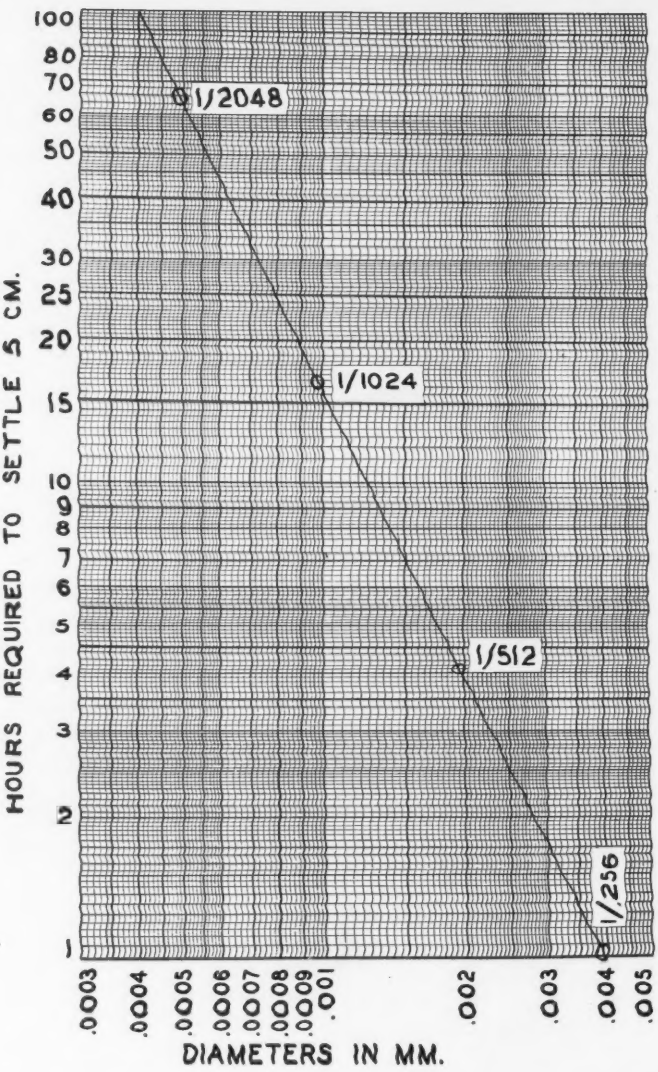
A double logarithmic time chart, showing the relation between diameters in millimeters, and time in hours for settling a given distance, is offered for the convenience of sedimentary petrologists. Details of construction are briefly mentioned.

The writer's experience shows that in making mechanical analyses by the pipette method it is occasionally inconvenient to sample the suspension at exactly the time needed for a particular Wentworth-scale diameter. Since the intervals of settling vary from a few minutes to a number of hours, this is particularly true of the longer intervals. In addition, it is often desirable to obtain data on diameters intermediate to those along the Wentworth grade scale. Hence a graph was made which shows the relation between diameter and settling time as a linear function, so that interpolation for any intermediate values becomes a simple matter of reading a straight line graph.

Figure 1 shows such a graph, covering the range from 1/256 to below 1/2048 mm. diameter. It is drawn on ordinary double logarithmic paper, and the diagonal straight line shows the relation between diameters and time. The several computed values on which the line is drawn are shown by circles which represent the Wentworth-scale diameters along the range included. The time scale has a decimal division of hours, which occasions no difficulty when it is recalled that 1/10 of an hour is 6 minutes. A similar graph based on larger diameters and time in minutes may also be made, but for a similar accuracy it is necessary to use a rather large scale sheet.

Figure 1 starts at the one hour point, and was based on a settling distance of 5 cm. to increase its range in the smaller sizes. It may be preferable to use 10 cm. as a standard depth of sampling for most pipettings and in that case the time read on the scale is merely doubled. Thus, the 1/512 mm. size corresponds to a settling interval of 4.1 hours for 5 cm., which is equivalent to 8.2 hours at 10 cm. This linear relation between time and depth of settling follows from the equation $v = h/t$, in cases where the velocity v is constant, as it is for a given diameter.

The principle on which the graph is based is quite simple. By Stokes'



law of settling velocities, the velocity varies as the square of the radius, $v = Cr^2$, where C is a constant and has the value 3.57×10^4 under the conditions that water at 20° C. is used, and assuming a mean specific gravity of the sediment equal to 2.65. The velocity, however, is also equal

TABLE I. *Time Scale for Pipette Analyses*[1]

Diameters in Millimeters		Velocity in cm./sec.	*h* in cm.	Hrs.	Min.	Sec.
1/16	0.0625	0.347	20	0	0	58
	.0442	.174	20	0	1	56
1/32	.0312	.0869	10	0	1	56
	.0221	.0435	10	0	3	52
1/64	.0156	.0217	10	0	7	44
	.0110	.0109	10	0	15	
1/128	.0078	.00543	10	0	31	
	.0055	.00272	10	1	1	
1/256	.0039	.00136	10	2	3	
	.00276	.00068	10	4	5	
1/512	.00195	.00034	10	8	10	
	.00138	.000168	10	16	21	
1/1024	.00098	.000085	5	16	21	
	.00069	.000043	5	32	42	
1/2048	.00049	.000021	5	65	25	

[1] The values in this table are based on a temperature of 20° C., and an average specific gravity of the sediment equal to 2.65.

to the depth divided by the time, $v=h/t$. The right hand sides of the equations may be set equal to each other, yielding $Cr^2=h/t$, and solving for t, we have $t=h/Cr^2$. By taking logs of both sides, and combining the constant terms (C and h) into a single term k, we obtain $\log t=\log k-2\log r$. When such an equation is plotted on double logarithmic paper, it becomes a straight line of slope -2, as the figure shows.

The chart as reproduced in Figure 1 is sufficiently accurate for pipette samples in the range shown. For a greater accuracy the graph may be constructed on a larger scale sheet. Similarly, some may wish to prepare graphs for larger diameters. For these purposes the diameters and times are shown in Table I. The table includes all diameters from 1/16 to 1/2048 mm., according to the grade scale based on the square root of 2, and supplements the earlier table offered by the writer.[1] Seconds are neglected beyond 1/64 mm.

In analyzing fine-grained sediments, the writer has adopted a standard routine that may be of interest to others. Pipette samples are taken at each of the Wentworth-scale diameters from 1/32 to 1/1024 mm. The cumulative curve is sketched from these data, and intermediate points are determined in the steep parts of the curve, according to the values in the table. Likewise, if less than 75 per cent of the size distribution is known by the time the 1/1024 mm. size is reached, one or more points below 1 micron are determined. An error is introduced into the results by taking these intermediate samples after the entire range is pipetted, because the suspension contains relatively more coarse material than it did originally. The error is often negligible, but in general it is well to run duplicate analyses for check.

[1] This *Journal*, vol. 2, p. 124, 1932. A typographical error occurs in the table, in that the hours corresponding to 1/2048 mm. should be 65 instead of 49.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 5, NO. 2, PP. 96–105, FIG. 1, TABLES I–III,
AUGUST, 1935

PETROGRAPHIC CHARACTER OF THE PENNSYLVANIAN SANDSTONES IN THE ARDMORE BASIN[1]

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Phillips University, Enid, Oklahoma

ABSTRACT

A mineralogical study of the sandstones of the Pennsylvanian of the Ardmore Basin, especially those of the Springer formation, was made in the hope of establishing a foundation: (1) for reliable petrographic correlation; and (2) for securing mineralogical data concerning the source of the sediments. A brief analysis of the petrographic character of the sediments is presented, after which tentative conclusions are drawn as to petrographic correlation of the sandstone members and their probable source.

The Ardmore Basin is the region in southern Oklahoma around the city of Ardmore. The basin is made up largely of marine Paleozoic strata and is bounded on the north by the Arbuckle mountains and on the south by the Criner Hills. (Page 4, Plate I.)

The writer wishes to express his appreciation for the guidance in the investigation and the kindly criticism of this paper to Dr. S. Weidman of the University of Oklahoma. Thanks also are due Dr. C. W. Tomlinson of Ardmore for generous aid in giving information concerning the location of the cross sections from which samples were collected and for other assistance and information concerning the local geology in the Ardmore basin.

The geologic literature relating to the Ardmore basin gives excellent information on the stratigraphy and structure, but nothing seems to have been published bearing upon the petrography (micro-mineralogy) of the sediments in the basin. Descriptions of the geology have been published by Taff,[2] Goldston,[3] Girty,[4] Roundy,[5] Waters[6] and Miser.[7] The following description of the stratigraphy is based on the work of others, particularly the recent work of Tomlinson.[8]

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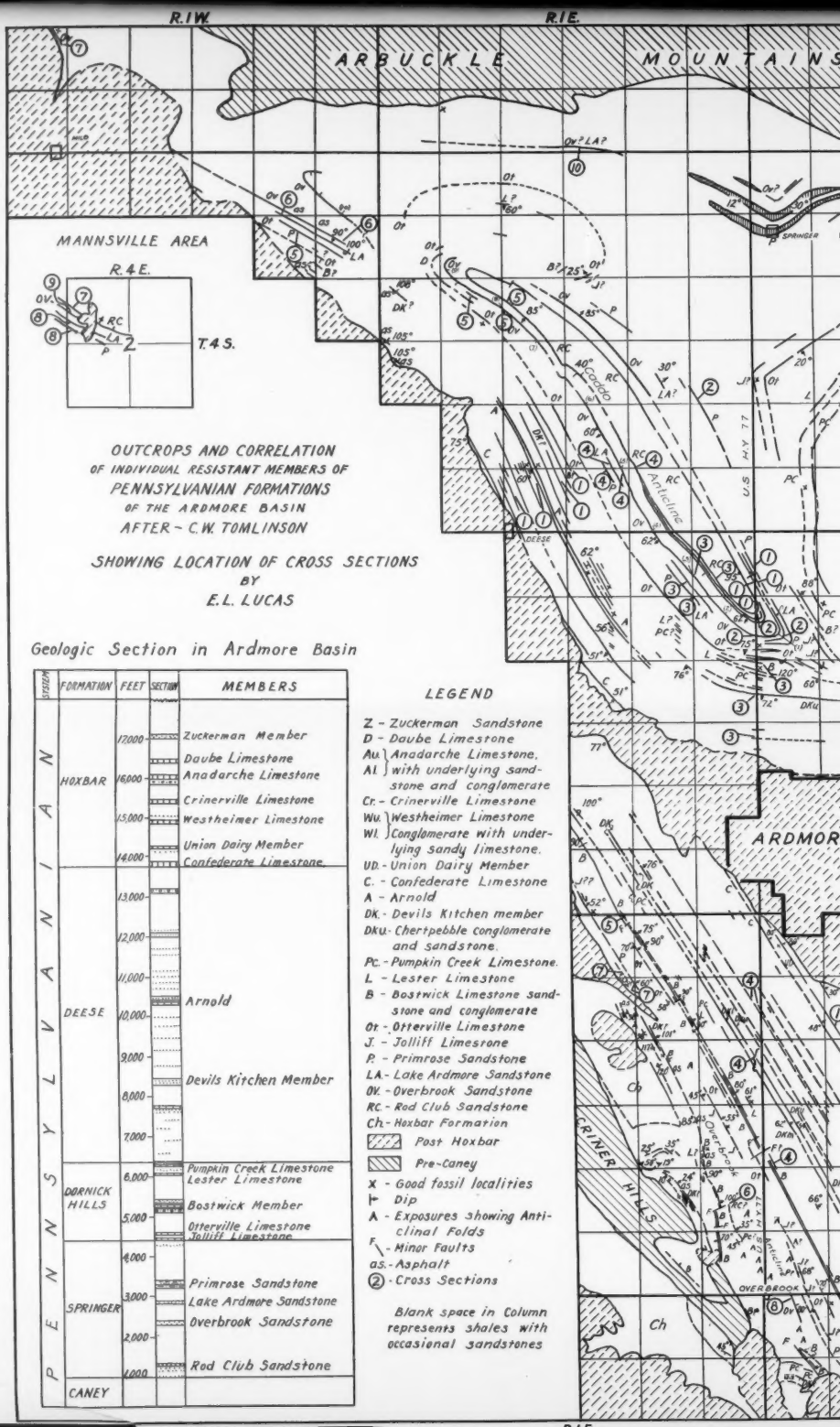
R.1W.
R.1E.
ARBUCKLE
MOUNTAINS
MANNSVILLE AREA
R.4E.
T.4S.
OUTCROPS AND CORRELATION
OF INDIVIDUAL RESISTANT MEMBERS OF
PENNSYLVANIAN FORMATIONS
OF THE ARDMORE BASIN
AFTER - C.W. TOMLINSON
SHOWING LOCATION OF CROSS SECTIONS
BY
E.L. LUCAS
Geologic Section in Ardmore Basin
SYSTEM
FORMATION
FEET
SECTION
MEMBERS
PENNSYLVANIAN
HOXBAR
DEESE
DORNICK HILLS
SPRINGER
CANEY
17,000
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10,000
9,000
8,000
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6,000
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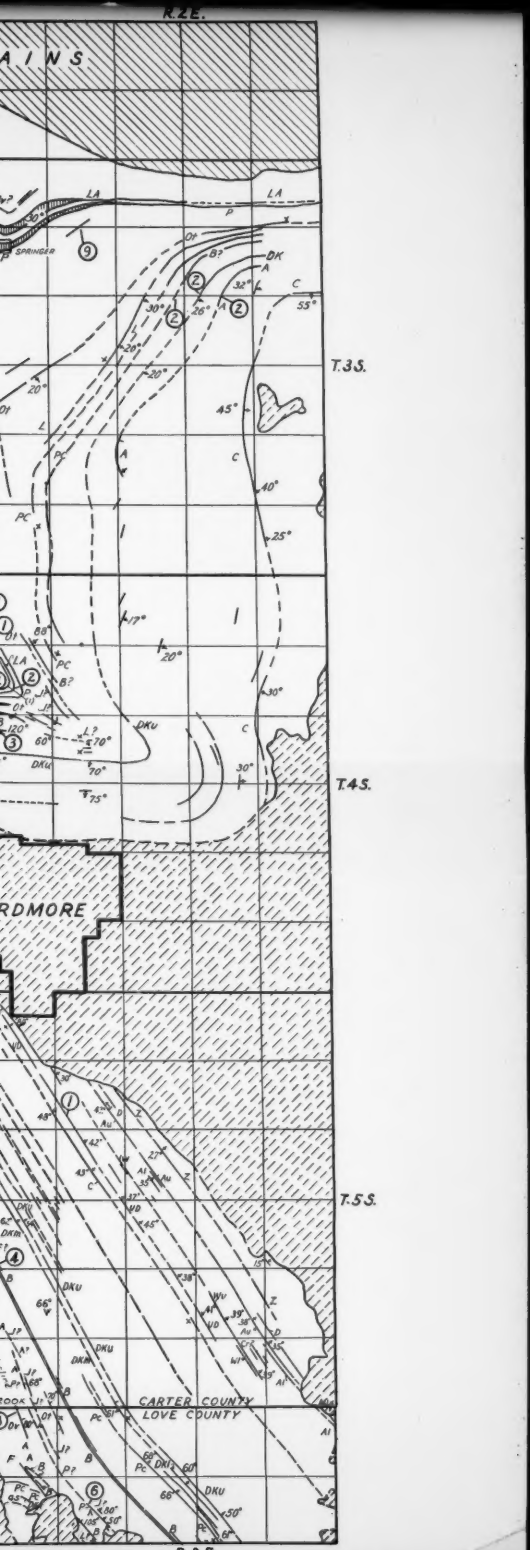
2,000
1,000
Zuckerman Member
Daube Limestone
Anadarche Limestone
Crinerville Limestone
Westheimer Limestone
Union Dairy Member
Confederate Limestone
Arnold
Devils Kitchen Member
Pumpkin Creek Limestone
Lester Limestone
Bostwick Member
Otterville Limestone
Jolliff Limestone
Primrose Sandstone
Lake Ardmore Sandstone
Overbrook Sandstone
Red Club Sandstone
LEGEND
Z - Zuckerman Sandstone
D - Daube Limestone
Au, Al - Anadarche Limestone, with underlying sandstone and conglomerate
Cr. - Crinerville Limestone
Wu, Wl - Westheimer Limestone Conglomerate with underlying sandy limestone.
UD. - Union Dairy Member
C. - Confederate Limestone
A - Arnold
DK. - Devils Kitchen member
Dku - Chertpebble conglomerate and sandstone.
Pc. - Pumpkin Creek Limestone.
L - Lester Limestone
B - Bostwick Limestone sandstone and conglomerate
Ot - Otterville Limestone
J. - Jolliff Limestone
P. - Primrose Sandstone
LA - Lake Ardmore Sandstone
OV. - Overbrook Sandstone
RC - Red Club Sandstone
Ch - Hoxbar Formation
Post Hoxbar
Pre-Caney
X - Good fossil localities
Dip
A - Exposures showing Anticlinal Folds
Minor Faults
as. - Asphalt
(2) - Cross Sections
Blank space in Column represents shales with occasional sandstones
ARDMORE
CRINER HILLS
OVERBROOK
SPRINGER
DEESE
Arbuckle
HWY 77
U.S.
R.1E.


R.2E.
AINS
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DKU
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TILDEN FOUNDATIONS
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DESCRIPTION OF THE SECTION

Due to complex folding and later erosion, the Pennsylvanian system is exposed in many places in the basin (Plate I). It consists from the base upward of the Caney, Springer, Dornick Hills, Deese and Hoxbar formations, and has a maximum thickness of 15,000 feet. The Springer formation consists of 3,000 to 3,500 feet of sandstones and shales. Below the Springer there are about 500 to 1,000 feet of the upper part of the Caney shales which usually are considered basal Pennsylvanian. The Dornick Hills formation is composed of conglomerates, sandstones, shales and limestones ranging in thickness from 1,000 to 4,000 feet. The Deese formation consists of chert conglomerates, sandstones, shales and limestones. The thickness ranges from 6,000 to 7,000 feet. The Hoxbar formation consists of sandstones, shales and limestones and has a thickness of about 4,000 feet.

PROCEDURE

The forty-nine localities from which over two hundred samples[9] of the sandstones were collected represent cross sections extending across the steeply inclined strata of each sandstone member. The cross sections are shown on the map, Plate I. Each sample was analyzed for the light and heavy mineral content, the size-grade distribution, the shape of detrital grains and the solubility in acid. The mechanical analyses show that sand grains ranging in size from 0.149 mm. to 0.074 mm. make up about 71 per cent of the sandstones. The light and heavy minerals of this size received the greatest microscopic study.

SPRINGER FORMATION

The Springer formation consists of four prominent sandstone members separated by thick beds of black shale. The Rod Club sandstone is the basal member.[10] About 1,000 feet of shale lie between the Rod Club and the overlying Overbrook sandstone. This is succeeded by approximately 500 feet of shale, which in turn are overlain by the Lake Ardmore sandstone. The Primrose sandstone is separated from the Lake Ardmore by about 500 feet of shale. The uppermost division of the Springer formation consists of about 1,000 feet of shale.

Rod Club Member.—The Rod Club sandstone contains four or five resistant beds and is buff in color and fine- to medium-grained. All samples collected are non-calcareous. The thickness ranges from 250 to 400 feet.

Overbrook Member.—The Overbrook member is typically a massive-bedded medium- to fine-grained gray, non-calcareous sandstone. Ripple marks occur locally. The thickness ranges from 40 to 100 feet.

Lake Ardmore Member.—The Lake Ardmore sandstone is typically a medium- to fine-grained light gray sandstone of which a few samples are calcareous. Its thickness is commonly 15 to 20 feet.

[9] The mineralogical data concerning each sample, locality and cross section is presented in the unpublished thesis.

[10] Tomlinson, C. W., *Op. cit.*, p. 12, 1929.

Primrose Member.—The Primrose member is usually a fine- to medium-grained dark gray, hard, generally calcareous sandstone. It contains numerous small lenticular streaks of dark colored shale which are parallel to the bedding. The thickness ranges from 150 to 200 feet.

Minerals.—The shape analyses involve a study of the light minerals which are chiefly quartz and feldspar. The average degree of sphericity of the 0.149 mm. to the 0.074 mm. size ranges from about two per cent in the Rod Club to a small fraction of one per cent in the Primrose. The studies indicate that the degree of sphericity increases with the increase in size of grains and that the shape depends upon the size-grade.

The soluble material is mainly calcareous and ranges from 0.6 per cent in the Rod Club member to 3 per cent in the Primrose. The distinctly calcareous samples of the Primrose are limited to the Caddo anticline.

The heavy minerals of the Springer sandstones are shown in the following table:

TABLE I. *Average Heavy Mineral Analysis of Springer Members*

Minerals	Rod Club	Overbrook	Lake Ardmore	Primrose
Leucoxene	53.6	54.2	56.1	49.1
Opaque Minerals	7.9	12.0	7.5	7.8
Zircon	11.9	8.1	8.1	11.8
Tourmaline	21.4	15.7	14.3	7.2
Garnet		.3	.08	.06
Rutile	1.4	1.5	.7	1.0
Staurolite	.6	.5	.3	.1
Chlorite	2.9	7.7	13.0	22.8

Leucoxene is abundant and averages about 50 per cent of the heavy minerals. Its monotonous occurrence is of little or no value in differentiating the Springer members.

The opaque minerals, ilmenite and iron oxides, vary greatly in frequency. Ilmenite is the most common.

The brown and green varieties of tourmaline predominate. Blue tourmaline is common in the Overbrook, but it is rarely found in the other three members. A few of the prismatic grains have vertical striations and many grains have numerous needle-like to globular inclusions. The inclusions are glass-like in appearance and are not oriented in any definite direction.

The zircon is of the colorless and glassy type and usually exhibits some degree of sphericity. The terminations of prismatic grains are usually round and some grains appear to be more or less rounded fragments. Striations and zoning characterize a few well preserved crystals and globular to needle-shaped inclusions are generally present.

A uniform increase in chlorite from the Rod Club to the Primrose is shown in Table I. The optical properties of this mineral vary so widely that precise identification is difficult. It is in very thin and flaky particles and is not easily detected except

when viewed between crossed nicols, where it shows partial extinction which varies from wavy to splotchy. The cleavage flakes are sub-angular to sub-rounded.

A few particles of colorless, angular-shaped, platy fragments of garnet were noted in the Overbrook member but were very rare in the Lake Ardmore and Primrose members. It was not found in the Rod Club member. The surface of these platy fragments exhibits a pitted and etched appearance. They are characterized also by high relief and some show low interference colors.

Rutile occurs sparingly. It always exhibits an amber color and usually shows some degree of sphericity. The prismatic forms usually show the characteristic striations due to twinning. Three knee twins were found in the Rod Club member.

Staurolite is rare but occurs in most samples. It is characterized largely by an irregular outline marked by a saw tooth-like fracture on two opposite edges. The fragments are more or less platy and exhibit a straw-yellow color. Irregularly shaped inclusions are common.

A study of the heavy minerals in the samples of the first three members reveals an interesting tourmaline-zircon ratio in passing from the base to the top of each member. The ratio in the lower zone of the Rod Club, Overbrook and Lake Ardmore is about 1 to 1; in the middle zone of each member about 2 to 1, and in the upper zone about 3 to 1. This ratio, however, is reversed in the Primrose, where it is about 3 to 2 in the lower zone; about 2 to 3 in the middle zone, and nearly 1 to 3 in the upper zone.

The light minerals are quartz and rarely a little feldspar. Many of the quartz grains show needle-like to globular shaped inclusions. Frosted grains and grains with secondary growth are rare.

Yellowish-green glauconite in the form of irregularly shaped grains or aggregates is present in a few samples but apparently is not distinctive of any certain stratigraphic horizon or locality. Much of the glauconite however, may have been decomposed in the preliminary treatment of samples with hydrochloric acid.

CORRELATION OF THE SPRINGER MEMBERS

The Springer sandstones may be differentiated from one another by their heavy minerals as shown in the table at the top of the next page.

The tourmaline to zircon ratio is significant in differentiating between the lower, middle and upper zones of the Springer sandstones. This ratio not only helps in demarcating the three zones of each member, but also aids in differentiating the Primrose from the Rod Club, Overbrook and Lake Ardmore members. The presence or absence of garnet, blue tourmaline and chlorite is also an important aid in correlating the members, as shown in Table II. The size-grade, especially for grains larger than those passing the 200-mesh screen and showing an increase in fineness from the Rod Club to the Primrose, may also be used for correlation. When the relationship of the several diagnostics is

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TABLE II. *Diagnostic Minerals of the Springer Sandstones*

		Rod Club	Overbrook	L. Ardmore	Primrose
Ratio of Tourmaline to Zircon	Upper	3:1	3:1	3:1	1:3
	Middle	2:1	2:1	2:1	2:3
	Lower	1:1	1:1	1:1	3:2
Garnet		none	common	rare	rare
Blue Tourmaline		rare	common	rare	rare
Chlorite		scarce	common	abundant	flooded
Per cent of grains between .42 mm. and .074 mm.		83	76	68	55
Silt, clay and soluble		17	24	32	45

Rare—an occasional grain; scarce—less than 1 per cent; common—1 to 5 per cent; abundant —5 to 20 per cent; flooded—over 20 per cent.

considered, it furnishes additional aid in correlation.

DORNICK HILLS FORMATION

Bostwick Member.—This member is made up largely of sandstone, limestone and limestone conglomerate. The most distinctive feature is the limestone conglomerate which becomes rapidly coarser in going from Ardmore towards the Criner Hills. The maximum thickness is about 500 feet.

Minerals.—Leucoxene is quite variable in quantity, ranging from 11 to 84 per cent of the heavy minerals. The color is yellowish-white and the grains are rough and irregularly shaped. The other opaque minerals show a wide quantitative variation.

Colorless zircon is present in all samples and zoning is present in a few grains. Most of the zircon grains are quite spherical and some appear to be rounded fragments.

The brown variety of tourmaline is the most common, the green variety is fairly common and the blue occurs occasionally. A few nearly colorless tourmaline grains show distinct vertical striations. Irregular and globular-shaped inclusions in the tourmaline are numerous.

Rutile is characterized by an amber to straw-yellow color and twinning striations. The grains vary in shape from spherical to well preserved crystals.

Gray garnet is common. Most grains are angular to subangular platy fragments. The surface is characterized by a somewhat etched and clouded appearance.

Staurolite is not common and that present has a straw-yellow color, numerous inclusions and a somewhat platy form with a very striking hackly fracture on opposite sides.

Chlorite is relatively scarce. The grains occur in the form of thin cleavage flakes. The color is a very pale-green and between crossed nicols the appearance is splotchy.

The light minerals are mainly quartz with about 6 per cent feldspar. The occurrence of considerable feldspar in the Bostwick sandstone distinguishes it from the underlying

sandstones of the Springer. Angular chert fragments were observed in cross section 4 among the light minerals and ranged from 0.42 mm. to the 0.074 mm. size.

DEESE FORMATION

Devil's Kitchen Member.—The lowest member of the Deese formation has been termed the Devil's Kitchen sandstone. This is about 500 feet thick. The lowest 150 feet or more of this member is a medium-grained buff colored sandstone. The upper part is separated from the lower by calcareous shales and a few feet of limestone and consists of a thick sandstone containing chert fragments ranging to one-half inch in diameter. The upper portion thickens southeastward and develops into a coarse chert conglomerate about 12 miles southeast of Ardmore.

Arnold Member.—The Arnold member occurs near the middle of the Deese formation and has a thickness of about 150 feet. The lower 50 feet are limestones, the middle 50 feet are shales and the upper 50 feet are medium-grained, massive, buff colored sandstones.

Minerals.—The heavy minerals are very similar to those of the Dornick Hills. The mineralogical comparison indicates a higher per cent of opaque minerals in the sandstones of the Dornick Hills than in the Deese, but the percentage of leucoxene is higher in the Deese.

The light minerals are largely quartz with about 6 per cent feldspar. Angular rock fragments, mostly chert, are present in all samples of the Deese and range in diameter from 0.42 mm. to 0.074 mm.

HOXBAR FORMATION

Union Dairy Member.—The Union Dairy member has a thickness of about 75 feet. The lower 20 feet are buff, medium-grained sandstones; the middle 30 feet are calcareous shales and the upper 25 feet are limestones with interbedded shaly layers.

Minerals.—The heavy mineral assemblage has distinctive features. A darker variety of leucoxene occurs than in any other sandstone in the basin. The garnet exhibits a clouded and etched surface. The tourmaline and staurolite contain crowded inclusions, which appear to minimize the amount of transmitted light. This dark character of the total assemblage is a feature observed only in the Hoxbar samples.

The light minerals consist largely of quartz with a marked increase of feldspar. The feldspar averages about 10 per cent and is largely microcline.

CORRELATION OF THE PENNSYLVANIAN FORMATIONS

The Springer sandstones usually contain less than 1 per cent feldspar (see Table III), whereas the sandstones (limited study) from the Dornick Hills and Deese contain from 5 to 7 per cent and the Hoxbar usually 9 to 11 per cent. The feldspar of the Springer is so sparse as to be determined with difficulty, whereas, it is very apparent in the overlying sandstones analyzed. The 9 to 11 per cent feldspar in the Union Dairy sandstone of the Hoxbar is mainly

TABLE III. *Diagnostics of the Pennsylvanian Formations*

Formations	Feldspar per cent of total	Garnet per cent of heavy mineral content	Rock fragments (mainly chert)
Hoxbar	9–11	6–7	none
Deese	5– 7	4–6	present
Dornick Hills	5– 7	4–6	present
Springer	0– 1	0–1	none

microcline, a species of feldspar not found in the other formations.

The average quantity of garnet in the Springer sandstones is less than 1 per cent of the heavy minerals. The samples from all cross-sections of the overlying Dornick Hills and Deese contain from 4 to 6 per cent and the Hoxbar contains from 6 to 7 per cent.

Angular rock fragments, identified in part as chert, are encountered in most samples of the Deese cross sections and in the Dornick Hills cross-section 4, south of Ardmore. They are lacking in the Springer and Hoxbar.

Conditions of Deposition.—The exact size and shape of the basin have not been completely defined. The fact that the quantity of Pennsylvanian sediments contributed to the basin was large is attested by the 15,000 feet of strata that are present. A study of the sediments together with field evidence seems to indicate an area undergoing depression with contemporaneous deposition.

SOURCE OF SEDIMENTS

The mineralogical study of the sediments suggests at least two possible sources of supply—Llanoria or local sources. Some geologists emphasize Llanoria as a probable source of the Springer sediments.

Miser[11] has presented evidence for the existence of Llanoria, based largely upon the thickness and structure of sediments, supposedly derived from that area. King's[12] map shows that the Pre-Cambrian crystalline rocks of Llanoria are probably connected with the Piedmont Plateau. Martens'[13] recent study of the persistence of feldspars in beach sand adjacent to the Piedmont Plateau shows that the quantity of feldspar present in the beach sand at Charleston, South Carolina, is about 6 per cent. The quantity present after the sand has been transported 350 miles along the shore to Cocoa Beach, Florida, is about 3 per cent. The feldspar grains still remain fresh and indicate that destruction is largely mechanical. If the sediments of the sandstones of the Springer were derived from crystalline Llanoria, the quantity of feldspar should be comparable to that now being derived

[11] Miser, Hugh D., Llanoria, the Paleozoic Land Area in Louisiana and Eastern Texas: *Am. Jour. Sci.* (5), vol. 2, p. 68, 1921.

[12] King, Phillip B., An Outline of the Structural Geology of the United States: *Int. Geol. Congress*, XVI session, Guide book 28, p. 18, 1933.

[13] Martens, James H. C., Persistence of Feldspar in Beach Sand: *Mineralogical Soc. Am. Jour.*, vol. 16, p. 526, 1931.

from the crystalline Piedmont and deposited along the Atlantic coast, since the distances of transportation are of the same order of magnitude.

The lack of feldspar and the prominence of the more stable minerals as zircon, tourmaline with sparing amounts of rutile, staurolite, garnet and iron oxides and the essential exclusion of other heavy minerals, implies derivation, according to Milner,[14] not from primary but from pre-existing rocks of sedimentary origin. The presence of very small quantities of garnet, staurolite and tourmaline indicates that they were also far more likely derived in previous sedimentary cycles from rocks of metamorphic origin. If Llanoria was a Pre-Cambrian crystalline land mass similar to the Piedmont Plateau, it seems highly questionable that it could have contributed the sediments of the Springer with its very low content of feldspar. More light will be thrown upon this paleogeographic problem when the rocks of Llanoria are more fully determined.

Concerning local sources, there may be considered a lowlying, slowly rising land mass in the Arbuckle and Criner Hills area, perhaps larger than the present outline, as supplying sediments to the basin during Pennsylvanian time. The meagre amount of feldspar in the Springer and the gradual increase through the Dornick Hills and Deese to 11 per cent in the Hoxbar is the kind of distribution of feldspar expected if the sediments were derived from the progressive denudation of the formations exposed in the Criner Hills, Arbuckle mountains and similar buried land masses of this region. The progressive erosion of the Arbuckle mountains and other land masses with contemporaneous deposition of Pennsylvanian sediments in the Ardmore basin, may be hypothetically considered in three stages. Each stage represents a short time in the period of deposition of the Pennsylvanian, as well as in the erosion of the slowly rising land masses of the Arbuckle uplift.

Stage 1. Close of the Springer.—At this time the Springer had been deposited as the products of erosion in chronological order of portions of the Caney shale, Sycamore limestone, Woodford chert, Hunton limestone, Sylvan shale, Viola limestone, Simpson formation and far into the Arbuckle limestone but had not reached the Reagan feldspathic sandstone. It is to be understood that only parts of each of these formations would be eroded, mainly from the stream valleys developed in the deeply dissected Arbuckle mountain uplift of that time. Studies of the rocks of the Arbuckle Paleozoic section show that they contain small crops of heavy minerals and very little feldspar and thus comparable to that present in the Springer.

Stage 2. Close of the Deese.—At this time the Dornick Hills and Deese had been deposited as a result of widening and deepening of valleys in the adjacent uplifted land masses. The presence of 5 to 7 per cent feld-

[14] Milner, Henry B., *Seidmentary Petrography*, p. 427, 1929.

spar in the Dornick Hills and Deese indicates the first important contribution from the feldspathic sandstone of the Reagen formation and possibly to some extent from the underlying Pre-Cambrian granite. The abundant chert fragments were probably derived from the woodford chert.

The heavy minerals of the Deese and Dornick Hills are very similar in character and occur in about the same order of abundance. Combined with feldspar and chert fragments, they suggest a common source of sediments throughout Dornick Hills and Deese times.

Stage 3. Unroofing of the Tishomingo Granite and Close of the Hoxbar. —A petrographic study of twenty-eight thin-sections of the Arbuckle granites made by Uhl[15] reveals microcline ranging from 15 to 50 per cent of the Tishomingo granite. The presence of 9 to 11 per cent of feldspar, mainly microcline, in the Hoxbar suggests still deeper erosion into the Arbuckle uplift and the unroofing of the Pre-Cambrian Tishomingo granite from which the abundant microcline in the Hoxbar may have been derived.

Views have been expressed as to the derivation of sediments from Llanoria, although no reference is made concerning the mineralogical composition of the sediments. Such views are based upon general lithological (distribution of the coarse and fine sediments), structural (variation in the thickness of beds) and stratigraphical (long range correlation of the strata) evidences. The question of the source of the sediments is necessarily involved with the date of the initial uplift of the Criner Hills and Arbuckle mountains. The date assigned to the initial uplift by most writers ranges from Late Mississippian to Early Pennsylvanian time, and after the uplift it suffered erosion through the remaining Paleozoic era. A few hold the view that the uplift occurred near the middle of the Pennsylvanian.

However, if the microcline of the Hoxbar formation has its source in the Tishomingo granite, the overlying Paleozoic group of rocks from the Mississippian down to the Pre-Cambrian had to be eroded away in order to unroof the Pre-Cambrian granitic rocks by Hoxbar time. Hence, the beginning of orogenic movements in the Arbuckle region may reasonably be dated near the close of the Mississippian or the beginning of the Pennsylvanian, and thus in harmony with the generally accepted view of widespread orogeny of that time.

CONCLUSIONS

The conclusions based upon the available petrographic evidences are tentative and are subject to subsequent modification if future research reveals additional mineralogical and field data.

(1) The four sandstone members of the Springer may be differentiated from one another by heavy mineral content, the key minerals being tourmaline, zircon, garnet and chlor-

[15] Uhl, B. F., Igneous Rocks of the Arbuckle Mountains, Thesis, University of Oklahoma, pp. 9–14, 1932.

ite. The four formations of the entire Pennsylvanian system of the Ardmore basin may be grouped into three divisions, distinguished mainly by relative abundance of feldspar, garnet and chert fragments.

(2) This petrographic investigation yields negative evidence concerning the contribution of sediments from Llanoria to the Ardmore basin during Springer and subsequent time and suggests the Arbuckle mountains, the Criner Hills and other possible uplifts buried beneath younger rocks as the source of the sediments.

(3) The petrographic evidence bearing upon the source of the sediments implies uplift of the Arbuckle mountains at the close of the Mississippian time and this interpretation is in harmony with the generally accepted views of the recognized widespread unconformity between the Pennsylvanian and Mississippian systems over the entire Mississippi valley.

Petrography of Sedimentary Rocks (*Textbook for mining schools: geologists' handbook*), M. S. Schwetzoff, Moscow, 1934, 374 pages, 34 pages of illustrations.

The work considers the problems associated with the study of sedimentary rocks and discusses the origin and morphology of sediments, particularly emphasizing the historical point of view. The book consists of five parts: (1) recent marine and continental sediments, (2) mineral and organic components of sedimentary rocks, (3) structures and textures, (4) description of the main types of sedimentary rocks, and (5) methods of study.

The relation of recent sediments to the corresponding sedimentary rocks is discussed in some detail. The author defines the term "macrotexture" as the texture of a bed or series of beds. Macrotextures such as laminae, concretions, ripple marks, stylolites, etc., vary as to origin, but reflect the history and influence the quality of the rock.

The author's classification of sedimentary rocks, stated to be based upon chemical and genetic principles is as follows: (a) clastic rocks (gravel, sand, and silt); (b) rocks resulting from chemical weathering (clays); and (c) chemical and biochemical rocks. The different types of sedimentary rocks are described and illustrated by examples from U.S.R.R.

The clastic rocks are classified as (a) coarse clastic, (b) sandy, and (c) fine-grained. The classification of sandy rocks is based upon mineralogical composition and they are divided into two groups. Rocks consisting of one to two dominant minerals are termed *oligomictic* and those composed of several minerals *polymictic* (arkose and graywacke). Oligomictic rocks are characteristic deposits of epicontinental seas and are rarely found in geosynclinal regions. Polymictic rocks are characteristic of geosynclinal regions.

Argillaceous rocks are placed in three chief groups: (a) residual products (bauxites, laterites, etc.), (b) transported unconsolidated argillaceous material, (c) transported consolidated argillaceous material (argillites).

Carbonaceous rocks are divided into four groups: (a) organogenous deposits, (b) chemical and bacterial sediments, (c) redeposited products of disintegrated carbonaceous rocks, (d) very fine grained or recrystallized rocks of questionable origin.

Siliceous rocks consist of (a) organogenous rocks, (b) altered rocks, partly organogenous, (c) chemical rocks, (d) siliceous segregations in other rocks.

The author discusses heavy mineral technic and describes the more important heavy minerals. Tables from Milner's "Sedimentary Petrography" are included. Most of the illustrations are taken from Cayeux.

The book is written in Russian, printed on low quality paper and is poorly bound. The review is based on a typewritten summary in English. The fact that the work is in Russian does not permit the writer to present any statement relating to its value.

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